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Control Technologies. Volume 1
Prevention and Protection Technologies for Controlling Accidental Releases of Air Toxics

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16. ABSTRACT The volume discusses prevention and protection measures for controlling accidental releases of air toxics. The probability of accidental releases depends on the extent to which deviations (in magnitude and duration) in the process can be tolerated before a loss of chemical containment. Developing a satisfactory control system and equipment capable of withstanding deviations requires adherence to sound process and physical plant design principles and to appropriate procedures and management practices. A process can be controlled by manipulating flow, temperature, pressure, composition, and quantity. A control system can be improved by improving the quality, specifications, and maintenance of physical components, and by duplicating components where warranted. The probability of equipment failure (causing a release) can be reduced by considering various aspects of physical plant design. Whereas process design involves process operating conditions, physical plant design involves hardware, equipment components, and their placement within a unit or plant. A third way to reduce the probability of a release is to maintain proper management practices and personnel training procedures. Finally, protection system technologies (e.g., flares, scrubbers, and enclosures) offer a last line of defense against accidental toxic chemical releases.

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Chemical Plants	Education	Stationary Sources	07A	15I
Emission	Management	Air Toxics	14G	15A
Toxicity		Chemical Releases	06T	
Chemical Compounds		Training	07B, 07C	
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CONTROL TECHNOLOGIES
VOLUME 1: PREVENTION AND PROTECTION TECHNOLOGIES FOR CONTROLLING ACCIDENTAL RELEASES OF AIR TOXICS

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ABSTRACT

A toxic chemical release occurs when equipment breakdown or loss of process control in a chemical process operation causes a loss of containment of the chemicals. The probability that an accidental release will occur depends on the extent to which deviations (in magnitude and duration) in the process can be tolerated before a loss of chemical containment occurs. Development of a satisfactory control system and equipment capable of withstanding deviations from the design intent requires adherence to the principles of sound process and physical plant design and to appropriate procedures and management practices.

Process design and control are intimately related. Control of a process is achieved by manipulating the variables of flow, temperature, pressure, composition, and quantity, for deviations in these variables can cause deviations from acceptable process conditions that would increase the potential for a toxic chemical release. A control system can be improved by improving the quality, specifications, and maintenance of physical components, and by duplicating components (the principle of redundancy) where warranted. Process changes that enhance control of the system will reduce the probability of a chemical release. Such changes include reducing the severity of operating conditions and modifying the basic chemistry, operations, and equipment.

The probability that equipment will fail and cause a release of toxic chemicals can also be reduced by considering various aspects of physical plant design. Whereas process design involves the operating conditions of a chemical process, physical plant design involves the hardware, the equipment components, and their placement within a unit or plant.

A third way to reduce the probability of a release is to ensure that proper management practices and personnel training procedures are maintained from the initial research and development through the manufacture of a chemical product. Finally, protection system technologies such as flares, scrubbers, and enclosures offer a last line of defense against the occurrence of accidental toxic chemical releases.

Each of these areas is discussed in terms of its relation to specific categories of hazards, its effectiveness in reducing the probability of a release, and the relative economics of its application.

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SECTION 1
INTRODUCTION

Accidental toxic chemical releases, fire, and explosion are the three types of major accidents in chemical process facilities. Toxic chemical releases may occur as the result of fire or explosion, but may also occur in their absence.

This manual, which addresses the prevention of and protection from accidental releases of toxic chemicals, is part of a three-part set of reference manuals whose purpose is to summarize the major concepts of release hazard control so that the probability and consequences of accidental toxic chemical releases can be reduced. The volumes in the series include:

Prevention Reference Manual - User's Guide
Prevention Reference Manual - Chemical Specific
Prevention Reference Manual - Control Technologies
    Volume 1: Prevention and Protection Measures
    Volume 2: Mitigation Measures

The PRM-Chemical Specific actually consists of a number of individual volumes for specific chemicals.

This series of manuals is intended to assist both regulatory and industry personnel in developing approaches to reducing accidental chemical releases and their consequences. In addition to highlighting the various technical aspects of the problem, the manuals also briefly address costs.

1.1 FUNDAMENTAL CONCEPTS

The purpose of preventing toxic chemical releases is to prevent harm to the health of human beings and other life and to the environment. An accidental toxic chemical release is the final event in a sequence of events leading to the release. In the terminology of formalized fault tree and event tree analyses, two of several formal methods for analyzing causes and effects in event sequences, that are discussed in the PRM-User's Guide, an event sequence begins with the initiating, or primary, event and passes along a chain made possible by enabling events. The chain is broken by preventing either the initiating event or the enabling events from occurring. Selection of the best of several possible options that could prevent a particular accidental toxic release depends on correctly identifying individual events and event chains, on knowing the relative probability of the events, and on the skill and knowledge of the individuals charged with solving the problem.

Figure 1-1 illustrates the place of prevention in the overall sequence of an accidental chemical release. Prevention is the second barrier between the realization of a toxic chemical release hazard and its consequences. It follows proper identification of the hazards. Protection, reduction of the quantity of material released, and mitigation, reduction of the magnitude of consequences, are two additional barriers. Community response is also shown as a barrier since community response measures can reduce the ultimate adverse consequences of a release. Evacuation is an example of a community response measure. Since the total prevention of an accidental release implies a zero probability for that release, and since this can never be assured, prevention in practice means reducing the probability of a release to within acceptable limits. At present, such acceptable limits, which are related to acceptable risk, are subjective and are not quantitatively defined.

Preventing accidental releases means preventing the loss of primary containment. The three general classes of equipment that contain chemicals are:

- Vessels;
- Piping; and

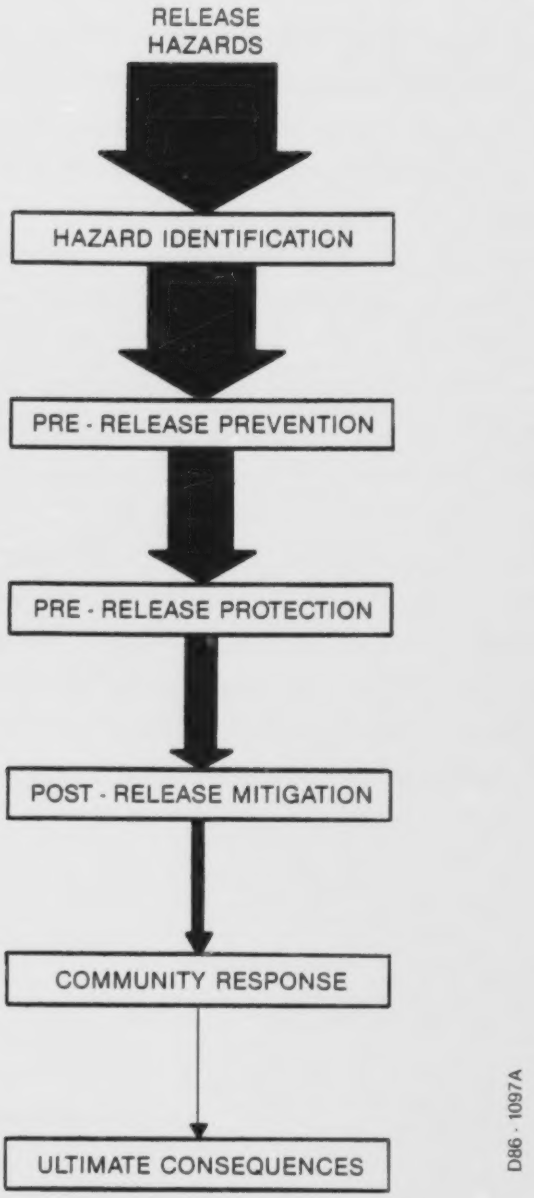
RELEASE HAZARDS
HAZARD IDENTIFICATION
PRE - RELEASE PREVENTION
PRE - RELEASE PROTECTION
POST - RELEASE MITIGATION
COMMUNITY RESPONSE
ULTIMATE CONSEQUENCES
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Figure 1-1. The role of various accidental release control measures in reducing the consequences of an accidental release.

- Process machinery.

In the context of this manual, vessels include all major process equipment: tanks, columns, heat exchangers, etc. Piping includes pipe lines, valves and fittings, and instruments fitted into pipe lines. Process machinery includes pumps, compressors, fans, and other such material moving equipment, either rotating or reciprocating. To ensure containment, a process must operate in proper sequence under acceptable conditions of temperature, pressure, and composition. The equipment must operate within design limits defined by specifications for pressure, temperature, externally applied mechanical stresses, chemical compatibility (corrosion, erosion), and within the physical limits imposed by the process system as actually installed and operated.

An accidental toxic chemical release can occur when there has been a physical breakdown of equipment or a loss of process control that leads to a breach in primary containment. Process modifications that enhance control and/or physical process steps and procedures that reduce the probability of equipment failure or a loss of process control will reduce the probability of a release. The overall problem, then, requires consideration of:

- Process design;
- Physical plant design;
- Operation; and
- Supervision or management.

The first two elements address the process, its chemistry, and hardware; the second two elements address the human factor.

1.2 ORGANIZATION OF THE MANUAL

Following this introduction, Section 1, the remainder of the manual addresses the above elements. Section 2, which covers process design considerations, addresess the basic functional and operational characteristics of any chemical process system, highlights major hazards associated with various characteristics of systems, and discusses the control measures that reduce those hazards. These include specific approaches for preventing deviations from intended operating conditions that could directly or indirectly cause an accidental toxic chemical release.

Section 3 covers physical plant design and considers how inappropriate design practices for the physical facility and its hardware contribute to accidental chemical releases. Adhering to proper design and equipment specifications for vessels, piping, valves, process machinery, and instrumentation can reduce the probability of an accidental toxic chemical release. Fundamental principles of configuration, layout and other design considerations associated with process hardware are discussed.

Section 4 discusses procedures and practices such as management policies, operator training, maintenance practices, and other topics. Some experts in loss prevention believe that the most significant decreases in the probability for accidental toxic chemical releases can be made in these areas.

Section 5 discusses protection systems, which include scrubbers, flares, and secondary containment systems. These devices, which can provide an emergency control system for process units handling some toxic chemicals, reduce the quantity of toxic chemical reaching the environment once primary containment has been breached.

A selection of hazard controls depends partly on the economics of their application. Example control costs are presented in each section for various process and equipment control technologies. These technologies involve individual hardware and procedural components, as well as multicomponent combinations for controlling an accidental release hazard. Since numerous combinations of individual controls are possible, costs are presented for individual hardware and procedural components that can be combined into a full control system.

Since costs in this manual are intended to be a starting point for initial planning, cost bases selected for each component are for specific sizes and overall specifications representative of that class of component. For example, for piping, one control option might be to use Schedule 80 rather than Schedule 40 pipe in some process unit. Costs are presented for three sizes of both Schedule 80 and Schedule 40 carbon steel pipe, two-inch, four-inch, and six-inch, which are common sizes encountered in many process plants handling toxic chemicals. While other sizes may be encountered, a first estimate of the relative costs of changing the schedule size can be estimated using one of these pipe sizes as an example.

The costs shown in this manual were obtained from various process plant estimating references and are presented in 1986 dollars. For each component, both capital and total annual costs are presented. Capital costs represent direct installed equipment costs, exclusive of indirect costs such as engineering or contractor's fees. Total annual costs include only labor where a procedure is involved, or only maintenance and capital recovery where a hardware component is involved. Maintenance costs for all hardware are assumed to be a flat two percent of the direct installed equipment cost. Capital recovery has been calculated at a 10 percent cost of capital over an assumed 10-year component life.

Costs for various controls applied to new plants can be expected to differ substantially from the same controls applied to existing plants. The relative differences in costs will vary according the type of controls, but, in general, retrofitted equipment is usually more costly than the same equipment installed initially. Costs in this manual apply to new plants. Retrofit costs can be roughly estimated as about fifty percent higher. Costs of introducing changes in procedures and practices can also be expected to vary, but generalizations about these costs cannot be as easily made as for equipment.

SECTION 2

PROCESS DESIGN CONSIDERATIONS

A first step in hazard control is planning the initial process design. This section describes the basic considerations of initial process design, as well as subsequent process modifications, and identifies operational aspects of a process where upset and loss of control could lead to a toxic chemical release. Process design considerations involve several fundamental principles applied to the process materials, process variables, and equipment. These principles are addition, substitution, deletion, and redundancy (or duplication). Each process chemical, operation, or piece of equipment should be viewed in terms of how changes based on these qualities may lead to a reduction in the probability of an accidental release. For example, substitution might involve the replacement of a toxic chemical with one less toxic. Duplication or redundancy might involve the use of a second thermocouple to measure a critical temperature.

Modifications, then, of fundamental process chemistry, operations, and equipment can reduce the severity of operating conditions, the quantities of toxic materials, the complexity of the process, and can enhance process control. Such modifications involve a number of process components:

- Control characteristics of the process;

- Process thermodynamics and chemistry;

- Flow measurement and control;

- Pressure measurement and control;

- Temperature measurement and control;

- Quantity measurement and control;
- Mixing; and
- Composition measurement and control.

Process hazards associated with each area that can contribute to accidental releases and the control measures that can reduce those hazards are discussed in the following subsections. Such measures may include changes in both hardware and operational procedures. Hardware changes may involve individual equipment items or entire systems. Costs of hardware components likely to be involved in process modifications are presented. Since process modifications can involve combinations of components, costs are presented on a component or subsystem basis, allowing the user of this manual to select those components that apply to any specific modification for which the user wants an approximate estimate of costs.

2.1 CONTROL CHARACTERISTICS OF THE PROCESS

Good process control, including the interaction of human operators with the process system, is basic to successful process operations. Process control is achieved by manipulating the variables of flow, temperature, pressure, composition, and quantity.

2.1.1 Process Control and Release Prevention

Adequate control of the process is fundamental to accidental release prevention, since loss of control might begin or propagate the sequence of events leading to loss of containment and accidental release. Loss of containment through loss of control occurs when some process variable exceeds the physical limits of the containment system. Equipment failure, operational failure, or both can cause loss of control. The interaction of human operators with the process is not explicitly addressed here, but certain aspects of the human factors, such as operator training, are discussed in Section 4.

Process control means maintaining process variables within prescribed limits. Process variables are either controlled directly or indirectly. Some indirectly controlled variables are maintained through control system action on directly controlled or manipulated variables. The physical characteristics of a process unit, the process chemicals, and the operating conditions determine the control characteristics of the particular system.

The following essential functions of a process control system may be modified to enhance control and reduce the probability of accidental releases:

- Measurement;
- Normal control; and
- Emergency or protective control.

These functions of a control system are the same whether manual, analog, or computer control is used. In any control system, the conceptual component configuration for controlling a variable is as shown in Figure 2-1. The connecting arrows indicate information flows between components. The dotted lines indicate that both direct or indirect measurement and control of variables is encountered in process systems. A sensor for the measurement device monitoring the measured variable transmits its signal to a controller, where a comparison or decision is made relative to specified process conditions. A signal is then sent from the controller to the actuator of a final control element, which adjusts the manipulated variable. In chemical process systems the most common manipulated variable is flow and the most common final control element is the actuator/control valve. The actuator is the device that physically operates the valve. The manipulated variable controls change in the measured variable. For example, a temperature might be the measured variable and flow of a cooling medium might be the manipulated variable. In some situations, the measured and manipulated variable may be the same: the flow rate of a fluid stream, for example. In a completely manual system, a human operator responds to a measurement and acts as both the controller and

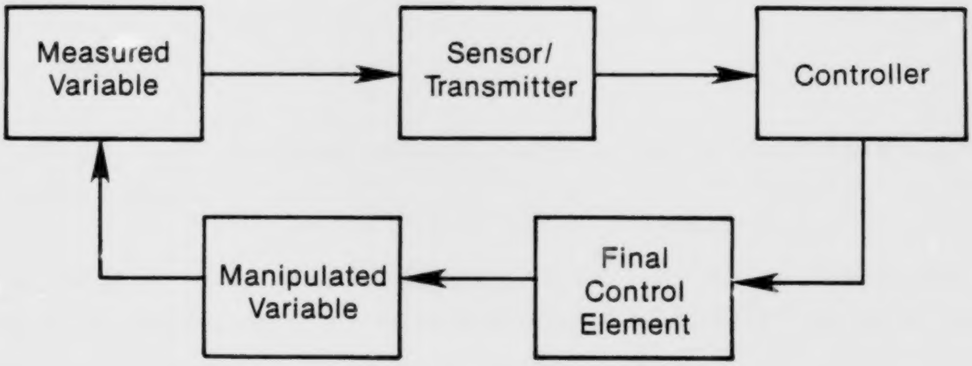
Measured Variable
Sensor/ Transmitter
Controller
Final Control Element
Manipulated Variable

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Figure 2-1. Generalized information flow for process control loop.

actuator of the final control element. In an analog system the response occurs through electrical, electronic and/or mechanical components. A computer system combines the components of an analog system with the capabilities of logic and computations software algorithms.

The primary variables for any chemical process unit are:

- Flow;
- Pressure;
- Temperature;
- Composition; and
- Quantity.

Typically, these variables are all controlled by manipulating the flow of some process stream.

The specified value of the controlled variable in the process system is referred to as its set-point. Deviations from this set-point can occur in response to various influences known as process loads.

Process loads may arise from disturbances in the following:

- Feed stream quality and rates;
- Service stream (e.g. steam, cooling water) quality and rates;
- Product stream quality and rates (especially where there is recycle);
- Equipment malfunctions;

- Process operating conditions;
- Ambient conditions; and
- Material properties and behavior.

Deviations in variables can cause deviations in the process. Deviations from acceptable conditions are the fundamental source of process hazards. A valve that is open when it should be closed or an overpressure leading to equipment failure or emergency venting are two examples of direct causes of accidental releases. The specific role of primary variables in process hazards is explored further in Sections 2.3 through 2.8. Certain additional general concepts of process control as they relate to hazard reduction are discussed below.

2.1.2 System Response

The overall control characteristics of a process depend on the response characteristics of both the process being controlled and on the control system itself. The response characteristics of a process are known as the process dynamics. The interaction of a control system with a process creates a new set of dynamic responses that may differ from the dynamic responses of the process alone. A key concept of process control and dynamics is that any corrective action taken will not result in an instantaneous response and might not result in the return of a deviating variable to its set point. The response of a system to a control action can result in a continued deviation, both in terms of duration and magnitude, or to new deviations, if a control system is not properly designed. Either the duration or magnitude of deviation may lead directly or indirectly to a loss of containment and to an accidental release. The relationship between deviations and specific causes of events leading to releases is the primary theme throughout other parts of this manual.

Any assessment of the probability of an accidental chemical release depends, therefore, on the extent to which deviations in magnitude and duration can be tolerated before a loss of containment occurs. Once this is known, the limits of control are defined, and appropriate initial design or modifications that enhance control can be undertaken.

2.1.3 Control System Integrity

The success of process control depends on the integrity of the control system. Integrity means that the control strategies and hardware are adequate, reliable, for the job at hand. Judging the adequacy of a control system requires examination of its components and specifications. An evaluation cannot fully determine adequacy, in terms of controller settings and response to system upsets, without understanding the intent of the basis for design, the design, or observing the control system in operation under actual process upset conditions. Partial insight can be achieved by examining the control system configuration on a piping and instrumentation diagram, the actual hardware used, by discussions with personnel familiar with operating the process, and by formal methods of hazard identification and evaluation such as hazard and operability studies and fault tree analysis, among others. Such methods should be used in control system design (1). From these approaches the control system's adequacy may be inferred.

If control strategy is correct, any increase in the reliability of a control system depends on improving the quality, specifications, and maintenance of the physical components, and on duplication of (redundancy) components where the potential hazard warrants. This may ultimately be a subjective decision; no specific criteria can be given here for that decision. The formal hazard evaluation method mentioned earlier can be a guide, however. For example, duplication could be applied to an entire loop, or only to the components most likely to fail. This judgement must be made on a case-by-case basis.

High points in design philosophy have been well-stated by one author (1). There should be a clear design philosophy and proper performance and reliability specifications for the control and instrumentation. The design philosophy should deal with, among other things, the characteristics of the process and of the disturbances to which it is subject, the constraints within which the plant must operate, the definition of the functions which the control system has to perform, the allocation of these between the automatic equipment and the process operator, the requirements of the operator and the administration of fault conditions. The philosophy and specification should cover measurements, displays, alarms, control loops; protective systems; interlocks; special valves (e.g., pressure relief, non-return, emergency isolation); the special-purpose equipment; and the process computer(s).

A process that appears to require a complex control system should be re-examined to determine process changes that would reduce the complexity.

The control system as a whole and the individual instruments should have the turn-down capabilities necessary to maintain good measurement and control at low throughputs.

Transient situations, such as startup, shutdown, and restarting after a trip or restarting an agitator, tend to be particularly hazardous.

2.1.4 Control System Components

Major control system components discussed in this section include:

- Sensing and measurement;
- Controllers;
- Final control elements;
- Switches and alarms;

- Emergency shutdown and interlock systems; and

- Computer control.

Certain aspects of control systems are general to the system as a whole or apply to all kinds of instrumentation used. Some important aspects are (1):

1. The control loops should have fail-safe action as far as possible, particularly on loss of instrument air or electrical power to the control valves. The action for other equipment should also be fail-safe where applicable. Control that adds material or energy should receive special consideration for integrity.

2. The ways in which common cause failure can occur and the ways in which the instrument designer's intentions may be frustrated should be carefully considered.

3. Instrumentation which is intended to deal with a fault should not be disabled by the fault itself. And if the process operator has to manipulate the instrumentation during the fault, he should not be prevented from doing so by the conditions arising from the fault.

4. The instrument system should be checked regularly and faults repaired promptly. It should not be allowed to deteriorate, even though the process operator compensates for this. The process operator should be trained not to accept instrumentation unrepaired over long periods.

5. Ease of detection of instrument faults should be an objective in the design of the instrument system. The process operator should be trained to regard detection of malfunction in instruments as an integral part of his job.

6. Instruments which are required to operate only under fault conditions, and which may therefore have an unrevealed fault, require special consideration.

7. Important instruments should be checked regularly. The proof test interval should be determined from a reliability assessment where possible. The checks should include measurements, alarms, control loops, etc.

8. Tests should correspond as nearly as possible to the expected plant conditions. It should be borne in mind that an instrument may pass a workshop test, but still not perform satisfactorily in the plant.

9. Valves, whether control or isolation valves, can leak even when closed. Control valves in particular may not give a tight shutoff. More positive isolation may require measures such as double block and bleed valves.

10. Valves, particularly control valves, also tend to stick, giving rise to conditions that do not always emerge from simple applications of the fail-safe philosophy. Two dangerous conditions are a feed valve jamming in an open position, or a cooling water valve jamming in a closed condition.

11. Practices which process operators tend to develop in their use of the instrumentation should be borne in mind, so that these practices do not invalidate the assumptions made in the reliability assessments.

12. The possibility of human error should be fully taken into account. The reliability of the process operator should be assessed quantitatively where possible. Human factor principles should be applied to reduce human error.

It is also necessary to pay careful attention to the details of the individual instruments used (1). Some important features are:

1. Instruments are a potential source of failure, either through a functional fault on the instrument or through a loss of containment at the instrument.

2. Use of inappropriate materials of construction can lead to both kinds of failure. Materials should be checked carefully in relation to the application, bearing in mind the possible impurities in the bulk chemicals. It should be remembered that the instrument supplier usually has only a very general idea of the application.

3. Instruments containing glass, such as sight glasses or rotameters, can break and give rise to serious leaks and should be avoided, where possible, with toxic chemicals.

4. Instruments may need protection against the corrosiveness of the process fluid. Examples of protection are the use of inert liquids in the connecting lines on pressure transmitters or of chemical diaphragm seals on pressure gauges.

5. Sampling and connecting lines should be given careful attention. Purge systems are often used to overcome blockage in sampling and connecting lines. Freezing is another common problem, which can be overcome by the use of steam or electrical heat tracing.

6. Temperature measuring elements should not normally be installed bare, but should be protected by a thermowell. A thermowell is frequently exposed to quite severe conditions, such as erosion/corrosion or vibration and should be carefully designed.

7. Pulsating flow is a problem in flowmeters such as orifice plate devices and can give rise to serious inaccuracies. This is a good example of a situation where duplication of identical instruments is no help.

8. Pressure transmitters and regulators are easily damaged by overpressure.

9. Complex instruments such as analyzers, speed controllers, vibration monitors and solids weighers are generally less reliable than other instruments. This requires not only that such instruments receive special attention, but that the consequences of failure be analyzed with particular care.

10. Different types of pressure regulator are often confused, with perhaps a pressure reducing valve being used instead of a non-return valve or vice versa. It is specially necessary with these devices to check that the right one has been used. Also, bypasses should not be installed across pressure regulators.

11. Selection of control valves is very important. A control valve should have not only the right nominal capacity but also appropriate rangeability and control characteristics. It should have any fail-safe features required, which may include not only action on loss of power but also a suitable limit to flow when fully open. It should have any necessary temperature protection (e.g. cooling fins). Bellows seals may need to be provided to prevent leaks. The valve should have a proper mechanical balance for the application, so that it is capable of shutting off against the process pressure. It should be borne in mind that any valve, but particularly a control valve, may not give completely tight shutoff, and also that a badly adjusted valve positioner can prevent shutoff.

12. Instruments should not be potential sources of ignition and should conform with the electrical area classification requirements.

A further discussion of the loss prevention aspects of control and instrument systems is given by Hix (2).

Sensing and Measurement--

Sensing and measuring both controlled and manipulated variables is fundamental to the proper operation of any control system. A wide variety of instrument types and vendors is available. Sensing and measuring devices include devices for normal process control, as well as trips and alarms for emergencies, and monitoring and detecting equipment for impending equipment failure and chemical leakage. Once a process system is constructed, its successful operation depends on the effectiveness of the sensing and measuring devices on which process control decisions are based.

Components for this function of the control system vary in sensitivity, range, accuracy, and reliability. Component selection must consider the severity of operating conditions, including chemical attack.

The variable of interest should always be measured directly where possible, rather than being inferred from some other measurement. The measurement should be made at the right location. If the variable is critical for process safety, the same measurement should not be used for control and for an alarm or trip.

Controllers--

The controller is the decision-making and command component of a process control system. The controller receives information from the process sensing and measuring equipment, compares this information with its set point, and takes appropriate action to minimize deviations. In a manual system, the human operator acts on the information. In a computer-supervised control system a computer acts on the information. Traditional analog control systems operate between these extremes.

Controllers come in a variety of types and operate in any or in all three common control modes: proportional, integral, and derivative; or in other specialized modes. Details of such features are beyond the scope of this manual but are widely discussed in the literature of process control (e.g., References 3, 4, 5). Pneumatic controllers have been available for many years and are still in wide use. Electronic controllers have grown in popularity over the years and include traditional analog electronic controllers as well as newer digital types.

The numerous changes in controller technology in recent years have created opportunities for both increased safety and hazards. Opportunities for safety exist because of the versatility, accuracy, and response capabilities of the newer generation of controllers. Opportunities for hazard result from the large number of available control systems, making inappropriate selection, application, installation and operation a greater possibility than before. Proper controller selection is an important step in accidental release prevention.

Final Control Elements--

A process control loop is completed with the final control element. In most cases this is a fluid control valve. In other cases it may be another device, an electric heater, for example. Again, many types and vendors exist. For a control valve, proper sizing, trim, and actuator selection are critical in selection since these factors determine how well the valve will perform its control function under both normal and abnormal operating conditions.

Switches and Alarms--

Switches and alarms are important devices for process upset and emergency conditions. Alarms are devices that warn of an impending or existing abnormal process condition; switches are action devices that divert a flow, close a valve, or perform some other emergency function such as tripping an alarm. Necessary characteristics are sensitivity to the condition being monitored and hardiness in hostile environments, especially because such devices are typically used only intermittently.

The most common of these devices respond to pressure, flow, level, and temperature. Details are described in the sections of this manual specific to each of these process variables, but certain general features are discussed here.

Switches may be indicating or non-indicating. An indicating switch has a scale readout that allows the process operator to make changes in the switch's set-point. A non-indicating switch is not adjustable by the process operator. This type may be appropriate in a process where the switch's function is crucial in controlling the potential for an accidental release and undocumented changes in the settings are to be avoided. The danger with this type, however, is that if process conditions are changed, the switch setting may also have to be changed, but there is no indication of the switch setting to verify that the necessary change has been made.

A switch should be applied to the parameter showing the most significant change for the condition to be alarmed to enhance switch sensitivity. For example, pressure switches are sometimes used in pump discharge systems to indicate a pump failure, or to start a spare pump. However, with a low-head pump system, the difference in pressure between the shutoff setting and operating pressure may be small, making switch operation unreliable. The change in flow rate between normal operation and shutoff condition may be significant, making a flow switch the better choice. Switches differ in their susceptibility to damage from overrange. This should be considered when selecting a switch for a process prone to overrange upsets.

The philosophy of the alarm system should relate the variables alarmed, the number, types and degrees of alarm, and the alarm displays and priorities to factors such as instrument failure and operator confidence, the information load on the operator, the distinction between emergency alarms and mere status indications, and the action the operator should take.

Emergency Shutdown and Interlock Systems--

These systems may use a combination of many instrument components to achieve a safe process shutdown condition. Their success depends on proper design and operating strategy, as well as on the proper selection of system hardware. An emergency shutdown system is used primarily for the shutdown of process equipment and for the operation of block, dump, and control valves. An interlock system presents a change in the operation of a pump, valve, or other equipment unless certain conditions are met. In the design of these systems, redundant components and circuits are normally recommended since these systems are safety systems and high reliability is a fundamental requirement. This is especially important in the temperature and level control of exothermic reactions or when heat sensitive materials are handled.

Instrument Air and Electrical Backup Systems--

Backup instrument air or electrical systems also should be provided for these systems. The backup electrical system for instruments and control may be part of the same system for general electrical backup, or it may be an independent system. Overall electrical backup can be achieved with diesel-generator sets. Sometimes the needs of critical process control instrumentation are best met by localized battery backup. These systems are often supplied as part of standard control instrumentation packages when the latter are purchased as a complete system, but can also be provided as packages for individual control loops, if required.

Where pneumatic systems are used, backup instrument air supplies may be system-wide or local. System-wide backup may require tying a main compressor into both the basic plant power supply and into the plant electrical backup system to ensure compressor availability during power outages. Another approach is to provide a large inventory of compressed air storage sufficient to bring a process system to a safe shutdown. Sometimes backup is provided by tying the instrument air into a liquid nitrogen system so that the nitrogen can be substituted for air on an emergency basis. Local backup of instrument air can be achieved by having a portable cylinder or emergency tank of either compressed air or nitrogen tied into the instrument air system for emergency use.

Computer Control--

The application of computer- and microprocessor-based control has increased rapidly over the last decade. There are at least two fundamental reasons for such growth: 1) reduced costs and a simultaneous increase in capability, and 2) hardware developments that permit more effective automated distributed control. An example of the former is the advent of microcomputers that offer a small operation true computer control for the first time. An example of the latter is the "smart" controller, a stand-alone controller that can be programmed for its various control functions and settings. A discussion of many more specific developments, including the use of coaxial cables to replace multiple cable runs between parts of a control system and a central computer, video screens to replace individual meters and displays in control rooms, and other such developments, is beyond the scope of this manual, but the reader may find ample information in the many books on process control and in technical periodicals (e.g., References 6 and 7).

The new instrumentation and control technologies offer an increase in the quality and quantity of data that can be handled at a given time. Two very desirable features are that priority scanning and rate of change monitoring can be employed. Such systems free the human operator from many routine and complex monitoring and evaluation functions, allowing him to focus on critical process deviations or upsets. Sequencing and the automatic shutdown features of such systems can make the system freer from operator error.

When computer systems are used, the ability to revert to manual control or ordinary analog control may be desirable in many processes for safety reasons. Such backup systems may be provided for the most critical parts of processes handling toxic chemicals.

2.1.5 Effectiveness of Control Systems

The effectiveness of a process control system is its ability to minimize the magnitude and duration of deviations in process variables. Maintenance of process variables at or near the set point is accomplished by direct manipulation of the flow of mass or energy into or out of the process unit. These manipulations alter the values of other variables. Loss of control, which can initiate the chain of events leading to an accidental release, can occur when manipulations fail in sequence, time of application, or magnitude. A fundamental loss of control can occur from a failure of components in the control system, including physical components and human error, or from faulty logical design of the control system. This latter failure is most likely to occur when deviations lead the control system to operate near or beyond the extremes of its design capabilities, in which case the design fault may be relative to the range of applicability rather than absolute. Proper design of the system and proper selection of individual components are therefore essential to ensure control system reliability and effectiveness.

The effectiveness of process control depends on the following key items:

- There are a limited number of fundamental manipulated variables for controlling any chemical process system.

- The controllability of a process depends on the interaction of both the process control system and the dynamics of the specific process.

- Critical variables should be measured directly. For example, a pressure indication should not be used as an indirect indication of temperature in an exothermic chemical reaction.

- The control system must be compatible with the level of training and skill of both operating and maintenance personnel.

- Duplication or redundancy of individual system components can increase the reliability of individual parts of the system.

- A redundant component must be completely independent of its duplicate.

- A definitive evaluation of process control for the critical variables in a process once a system has been installed is not easily accomplished by an evaluator and a judgement of its reliability must be inferred from limited information.

The reliability of the components that make up any control system has been studied for many common process equipment and instrumentation components (1, 8). One measure of reliability is the mean time between failures (MTBF), or the failure rate or frequency, the number of failures that occur per unit of time. Table 2-1 presents some values for selected components. Additional values are presented in other sections of this manual for specific equipment items. Such values can be used in conjunction with standard methods of quantitative systems analysis, fault tree analysis for example, to estimate overall system reliability.

Changes in control strategy or control system hardware may be an appropriate process modification to reduce the probability of a failure leading to an accidental toxic chemical release. However, a secondary hazard can be introduced if the effects of the changes on the process and its operation are not carefully reviewed beforehand. For example, although more sophisticated instrumentation and control schemes may be desirable in theory, in practice a lack of adequately trained or skilled operating or maintenance personnel may make such systems more hazardous. Direct process effects may include unforeseen changes in process dynamics.

TABLE 2-1. FAILURE RATES OF SELECTED PROCESS SYSTEM COMPONENTS

Component	Failure Rate (faults/yr)
Control valve	0.25 - 0.60
Differential pressure transmitter	0.76 - 1.73
Variable area flowmeter transmitter	0.68 - 1.01
Thermocouple	0.088 - 0.52
Pneumatic controller	0.29 - 0.38

Source: Adapted from Reference 1. More detailed information may be found in Reference 8 and other sources.

The following performance criteria should be considered when selecting components for process control systems:

- Mechanical or electrical;
- Range;
- Accuracy (repeatability);
- Precision;
- Operating environment and materials of construction;
- Sensitivity; and
- Ability to withstand excursions from specifications or operating conditions.

In summary, the process control system, which is understood to mean both the human operator and the control hardware, must be one of the key elements examined as a possible basis for process modifications to a process system. The specific modifications required must be made on a case-by-case basis but, in general, should be directed toward increasing the reliability and responsiveness of the control system to deviations and corrective actions for those variables most critical in preventing a loss of control. In the sections that follow, some of the specific fundamental principles of a chemical process, and pertinent process variables are explored in the context of possible process changes that could achieve the above objectives.

2.2 PROCESS CHARACTERISTICS AND CHEMISTRY

Numerous formal hazard identification and evaluation procedures are available which include examining chemical process characteristics and chemistry, as summarized in the PRM-User's Guide, that are amply discussed in the technical literature (9, 10). Fundamental process changes can often reduce inherent hazards by reducing in-process inventories of toxic materials and by reducing the severity of operating conditions. Some factors important in examining chemical processes for potential hazards are (1, 11):

- Inventory - the quantity of hazardous material in the process;
- Energy content - the inherent energy content specific chemical species as well as process temperature and pressure conditions;
- Time factor - maximum rate of a potential release, and warning time available for emergency counter measures;
- Substitutability - whether a less hazardous material can be substituted, or whether a substitution may result in less severe operating conditions; and

- Complexity - the number and kinds of process steps; the operational sophistication required for the process.

Hazard reduction through changes in these broad process characteristics involve other factors discussed below.

2.2.1 Process Materials

Evaluation of the properties of the materials in the process must include:

- Raw materials;

- In-process materials, such as reaction intermediates; and

- Product materials and process wastes.

The more known about all the materials in a process the better, but in practice, all potentially significant properties and even the identity of some intermediate process materials may not be known. Table 2-2 lists properties of significance for process hazards (12). For release prevention, the properties of toxic materials that should always be known are:

- Boiling point;

- Vapor pressure at ambient and process conditions;

- Specific heat;

- Heat of vaporization;

- Acute toxicity;

- Corrosiveness and reactivity properties;

TABLE 2-2. PROPERTIES OF MATERIALS TO BE CONSIDERED IN CHEMICAL PROCESS HAZARD EVALUATION

GENERAL INFORMATION REQUIRED

Corrosivity
Purity (Specifications of Grade Used)
Formula (Chemical Structure)
Contamination Factors (Incompatibility)
Quantity of Material Anticipated
Color
Hygroscopicity
Molecular Weight
Appearance
Odor
Physical State
Solubility
Synonyms

FLAMMABILITY INFORMATION REQUIRED

Flash Point
Fire Point
Flammable Limits
Specific Gravity
Vapor Density
Vapor Pressure
Heat of Vaporization
Boiling Point
Ignition Temperature, Autoignition Temperature
Spontaneous Heating
Dielectric Constant (Static Hazard)
Melting Point
Flow Point
Percent Volatiles
Extinguishing Media
Special Fire Fighting Procedures
Unusual Fire and Explosion Hazard
Gases Released During Decomposition
Heat of Fusion

REACTIVITY (INSTABILITY) INFORMATION REQUIRED

Differential Thermal Analysis (DTA)
Impact Test
Thermal Stability
Detonation with Blasting Cap
Drop Weight Test
Thermal Decomposition Test
Lead Block Test
Influence Test
Self Acceleration Decomposition Temperature
Card Gap Test
Thermal Stability (Under confinement) JANAF
Critical Diameter
Limiting Oxygen Value
Hazardous Decomposition Products
Incompatibility
Conditions Contributing to Hazardous Polymerization
Conditions Contributing to Instability
Shock/Friction Sensitivity
Decomposition Temperature
Specific Heat
Gas Evolution
Adiabatic Temperature Rise
Heat of Reaction

Source: Reference 12.

- Flammability; and

- Explosive limits.

The boiling point defines the physical state of the material in the process, whether it is a liquid or gas at ambient and process conditions, for example. The vapor pressure defines the volatility of the material when it is below its boiling point, and how much pressure buildup might be expected from overheating below the boiling point. The specific heat and heat of vaporization allow estimation of volatilization rates when the release occurs as a liquid.

Toxicity data alerts the designer, operator, or evaluator of a chemical process facility to what materials are most hazardous to health, and suggests where to focus attention when taking measures for release prevention. Parameters that should be considered include the IDLH, LC50, and others defined in standard chemical toxicity references.

Toxic materials that are also corrosive require extra care in specification of materials of construction and also in monitoring equipment conditions. Corrosive materials that are not the primary toxic materials in a process are also important; however, when they are involved in processes where toxics are present. Corrosion can contribute to equipment failure and to a toxic chemical release.

Unrecognized reactivity in a process can cause a release hazard. If certain materials are accidentally mixed, or unexpected contamination occurs, a runaway thermal reaction or violent evolution of gases can result. Both may cause overpressure or spillage of a toxic chemical.

Flammability and explosive limits are important because fires and explosions can cause an accidental release as well as be caused by a release of a flammable material. A small leak could result in a major release if ignited.

Other properties may be significant for other reasons. One example is density. In a two-phase non-miscible liquid system, the denser liquid will settle out in vessels and tanks if agitation is not provided. Another example is viscosity, which can be a significant variable affecting process behavior in flow, heat transfer, and mixing parts of a process. A special situation where this might contribute to a hazard is a loss of temperature control where emergency cooling might not respond as rapidly as expected because a viscous layer near a cool heat transfer surface reduced the heat transfer coefficient to a lower value than anticipated in the original process design. These are only some examples. Evaluation of process materials may have to take into account properties beyond those that at first appear obvious.

2.2.2 Process Mode

The mode of process operation can affect the safety of a process. Three basic modes of process operation are: 1) batch, 2) semibatch, and 3) continuous operation. Table 2-3 lists some considerations that apply to each of these modes.

2.2.3 Reaction Thermodynamics

The fundamental thermodynamic characteristic of concern for reaction safety is the exothermicity of a reaction. This is the direction and rate of energy release. An exothermic reaction releases heat and an endothermic reaction absorbs heat. Exothermic reactions are usually of concern because they can lead to thermal runaway reactions and the attendant adverse consequences. The hazard of a specific exothermic reaction depends on both the magnitude of the heat of reaction and on the rate at which the heat is released or absorbed. The magnitude is determined primarily by the specific reaction and by the quantities of chemicals involved. The rate depends on these variables as well as on the temperature at which the reaction takes place. The primary process consideration when exothermic reactions are present is provision of adequate cooling. Temperature control is discussed more completely in Section 2.5.

TABLE 2-3. CONSIDERATIONS FOR VARIOUS PROCESS MODES

	Batch	Semibatch	Continuous
Residence Time	Long	Long	Short
Feed System	Intermittent - short duration	Intermittent - long duration	Continuous - long duration
Startup - Shutdown	Frequent	Frequent	Infrequent
In-process Inventory*	Large	Large	Small
System Response			
Temperature	Slow	Slow	Fast
Pressure	Fast	Fast	Fast
Composition	Fast	Fast	Slow
Flow	Not applicable	Long	Fast
Fluid Dynamic Stability	Stable	Stable	Subject to Fluctuation

*At same annual throughput rate.

Endothermic reactions are not as hazardous as exothermic reactions, but do carry some hazard potential. Systems with endothermic reactions require heating. The hazard lies in the potential failure of the heating system in a way that would result in too much heat input to the process. This could cause overpressure through flashing, boiling, or expansion, and weaken or damage equipment.

2.2.4 Process Control System

Some fundamental concepts of control systems were discussed in Section 2.1. Types of control systems include:

- All manual,
- Manual/analog,
- Automatic/analog, and
- Automatic/digital, and
- Computer control.

The type of system used must be appropriate to the process. In general, reliability increases with sophistication, assuming proper design and installation.

2.2.5 Process Type

The type of process is characterized in terms of unit processes and operations. Certain unit processes and unit operations may be inherently more hazardous than others. The basic unit processes that make up most of the chemical industry have been defined in a classic work by Groggins (13) and more recently in a comprehensive study (14). Unit processes defined by the latter are presented in Table 2-4. Recognizing the class into which a process fits will highlight the specific hazard features associated with that class.

TABLE 2-4. UNIT PROCESSES IN THE CHEMICAL PROCESS INDUSTRIES

Acylation
Alkaline Fusion
Alkylation
Amination
Aromatization
Calcination
Carboxylation
Caustization
Chlorination
Combustion
Condensation
Coupling
Cracking
Diazotization
Double Decomposition
Electrolysis
Esterification
Fermentation
Halogenation
Hydration
Hydrocracking
Hydroforming
Hydrogenation
Hydrolysis
Ion Exchange
Neutralization
Isomerization
Nitration
Oxidation-Reduction
Polymerization
Pyrolysis
Reforming
Sulfonation

The most common unit operations of chemical engineering are listed in Table 2-5. Again, certain operations that may inherently be more hazardous than others can be considered for substitution in process modification.

2.2.6 Severity of Process Conditions

The severity of process conditions is defined by the levels of pressure and temperature for each step of the overall process, in reactors as well as separation equipment. The effects of pressure and temperature from a process hazard perspective are discussed in Sections 2.4 and 2.5. In general, the higher these variables, the more hazardous the process and the greater the accidental release potential. Pressures in excess of 1,000 psig may be considered extreme. Pressures above 400 psig and temperatures above 500°F may be considered high.

While severity is usually interpreted in terms of high pressure and temperature, extremely low conditions can also be hazardous. As discussed in Sections 2.4 and 2.5, these conditions require special precautions in design and operations. Conditions near ambient pressures and temperatures generally will result in safer operation than temperatures and pressures either much above or below ambient. Since operating conditions are usually determined by the fundamental chemistry of the process, changes in these conditions will require research into the corresponding changes in process chemistry. Important factors include the physical states of reactants, products and rate processes, fundamental reaction kinetics and rates of mass transfer. These factors of the process can be examined to determine where changes might reduce severity.

The history of methanol synthesis is an example of a situation where changes in the fundamental process reduced the severity of operating conditions. For many years the synthesis of methanol required high temperature and very high pressure. Research resulted in fundamental change to a new process that allows methanol to be synthesized at much lower temperatures and pressures (15); thus operation hazards were reduced.

TABLE 2-5. UNIT OPERATIONS IN THE CHEMICAL PROCESS INDUSTRIES

Absorption
Adsorption
Agglomeration
Centrifugation
Crystallization
Deionization
Desorption
Distillation
Drying
Evaporation
Extraction
Filtration
Heat Transfer
Leaching
Mixing
Membrane Transport
Size Reduction
Sublimation
Fluids Transport
Solids Transport

2.2.7 Process Complexity

Process complexity is characterized by the number of unit operations, streams, and variables that must be monitored and controlled in a process. In general, increased complexity increases the process hazard by creating more opportunities for unforeseen process interactions and more opportunity for errors in design, construction, and operation. Process complexity can be roughly estimated by considering the number of equipment items and the number of chemicals involved. A special consideration is how much recycling of process streams is in the process.

2.2.8 Process Modifications

Potential process modifications include any changes in the previously discussed areas that could reduce the toxicity, severity, sensitivity, or complexity of the process. Such modifications are limited by the fundamental constraints of process chemistry. The number and extent of possible modifications is probably greater the earlier in the development of a process they are made. An existing process offers less opportunity for fundamental change than a new process, but even here a change of catalyst, for example, might result in less severe, hence less hazardous, operating conditions.

The effects of modifications on traditional process costs will be process and plant specific. The effects will depend on equipment and operational features of the modified process. Though such costs cannot be estimated generically, some insight about the potential research and development costs of modifications can be gained by talking with technical and managerial personnel. It has been estimated that it costs about $150,000/year to maintain the average technical person in a large corporate environment. This translates into about $75/hour of researcher time. If it is assumed that this reflects the cost of the average technical professional/managerial person who would be involved in a program to modify the basic process characteristics and chemistry, the costs of such a program can be estimated from estimated levels of effort for the program. Figure 2-2 presents a range of costs for such programs based on average staff level commitment and program duration. Though these costs exclude lost production while modifications are being made or the capital investment required to physically modify a chemical process system, they illustrate order of magnitude costs that show that fundamental process modifications for process safety may equal the cost of new product/ process development and implementation.

Assume that a typical chemical product may take 5 or more years of effort and $10,000,000 to bring to market, excluding marketing costs. If a modification required only 10% of that effort, costs would be on the order of $1,000,000.

2.3 FLOW MEASUREMENT AND CONTROL

Flow measurement and control of both primary process fluids and service fluids such as steam, air, nitrogen, and heating and cooling media is at the heart of all process system operations. This section explores the role of fluid flow in process events that may lead to accidental toxic chemical releases, and flow hazard controls.

2.3.1 Flow Hazards

Process hazards associated with flow involve deviations that cause the flow to be too low, too high, reversed, or fluctuating. Flow changes may be caused by pressure changes in some prime mover for a fluid, or by changes in the resistance to flow in piping or other equipment. Special hazardous consequences of flow deviations can be identified for various individual equipment items and processes. Some consequences are obvious, while others are not. Some causes and hazards of loss of flow control are discussed below.

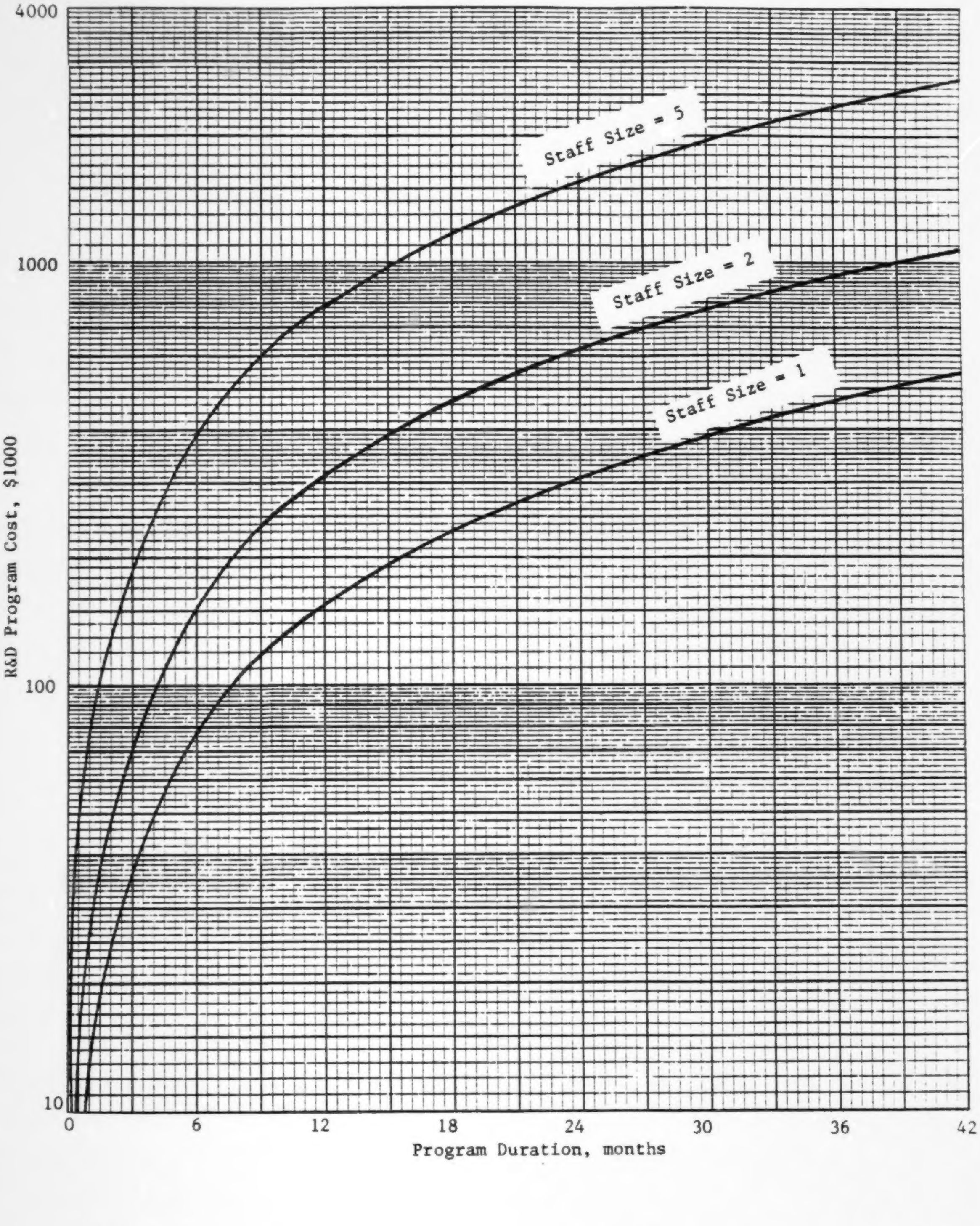


Figure 2-2. Estimated typical program costs for our R&D effort to develop process modifications.

Low Flow--

Flow can be interrupted or reduced by factors related to the process, equipment, or operations. These factors may act independently or in combination and include:

- Blockage;
- Vapor lock;
- Cavitation in pumps;
- Mechanical failures of prime movers; and
- Leakage.

Blockage can occur from physical obstructions such as dirt, tramp materials in a line, or deposits which build up over time. These include products of corrosion and erosion. Polymerizable fluids may cause blockage or restrictions to flow. Freezeup is another possibility with some materials.

Certain equipment especially prone to blockage includes all piping, especially small diameter piping and tubing, heat exchangers, packed beds, and filters. Support screens and perforated plates in process equipment are also prone to blockage. Control valves, which usually have orifices much smaller than line size, are especially prone to restrictions and blockage, as are orifices in differential pressure flow sensors. Control valves, being automatic devices, can sometimes jam in a full or partially closed position, due to such conditions as dirt buildup on the stem, or mechanical failure of the activator.

Vapor lock can occur when a gas or vapor collects in a line or other process equipment space so that the vapor pressure exceeds the available pressure head available for flow. Liquid flow through the line or equipment may be restricted or stopped.

Cavitation in pumping equipment can occur when a liquid near its boiling point or contains a dissolved gas. If the suction pressure to a pump falls low enough, the dissolved gas may be suddenly released or the liquid may boil, trapping a vapor bubble in the pump that causes the pump to lose suction and flow.

Mechanical failures in prime movers, such as pumps and compressors, are obvious causes of low flow. These mechanical failures include electrical outages as well as actual breakage of mechanical components.

Leakage upstream in a fluid system can cause deficient flow downstream. Causes of leakage are discussed in the subsections on equipment in Section 3 of this manual.

Many possible hazards are associated with low or no flow, depending on the process, but the following are typical:

- Overheating caused by inadequate cooling to a process. The consequences of excess temperature are discussed in Section 2.5. Some consequences include runaway chemical reactions or physical damage to equipment.

- Overcooling caused by inadequate heating to a process. The consequences of deficient temperature are discussed in Section 2.5. Some consequences include an accumulation of unreacted material that could cause a runaway reaction on reheating, a freezeup in a critical line, or collapse of an atmospheric vessel due to vapor condensation and unrelieved vacuum.

- Process upsets caused by incorrect feed rate. In some exothermic reactions a portion of the cooling relies on a low temperature feed. An increase in the feed temperature or loss of one feed and not the other can lead to an excess of one reactant. This can sometimes lead to an excess exotherm and a runaway reaction. Too low a feed rate to distillation columns can cause excess heating from a reboiler if the control system does not respond properly, causing overpressurization and a relief valve discharge.

- Low flow in a pump can cause overheating and pump failure.

Excess Flow--

A primary cause of excess flow is an open valve which should either be partially or completely closed. The following are some typical hazards associated with excess flow:

- Excess flow of a cooling medium can cause the same problems as deficient flow of a heating medium, discussed previously.
- Excess flow of a heating medium can cause the same problems as deficient flow of a cooling medium, discussed previously.
- As with low flow, incorrect reactant ratios can result, causing excess exotherms, or excess boilup and pressures in heated process equipment.
- Overfilling of vessels can result if excess flow is not detected and shut off in time.
- Unwanted siphoning of liquids is another example of excess flow; or flow where none is intended.

Reverse Flow--

Reverse flow can occur when downstream pressure exceeds upstream pressure. A common cause of reverse flow is a pump failure, or failure of a directly pressurized fluid transport system. Reverse flow is not uncommon, even in systems protected by check valves that may fail to close or seal properly. Some typical hazards of reverse flow are the following:

- Reverse flow can lead to unintended chemical or physical reactions. An unexpected exothermic reaction in a storage tank from backflow of process reactants is an example of a chemical reaction hazard. Overpressurization through unintended flashing of liquid is an example of a physical reaction hazard. This could occur, for example by reverse flow of a liquid into a heated process vessel. Unintentional contact of water and hot oil in refinery systems has sometimes caused steam explosions.

- Reverse flow through pressure relief vent headers can cause obstruction of vent lines, contamination by leakage through unseated pressure relief valves on other equipment connected to a common header, and excessive back pressure on relief devices, with all the attendant hazards that may result from these effects.

Fluctuating Flow--

Fluctuating flow can be caused by a variety of conditions. Reciprocating prime movers such as piston pumps inherently generate a fluctuating flow, but processes using such devices are either designed to accommodate the fluctuations, or have special dampers to reduce the fluctuations. Fluctuating flow may be a hazard when it is unintentional. Some common unintentional causes of fluctuating flow include cavitation in centrifugal pumps and improperly tuned automatic process control loops. Some hazards of fluctuating flow include:

- Severe pulsations which can damage piping and equipment. Even moderate pulsations over time may lead to fatigue failure in piping or other process hardware.

- The overall controllability of a process is degraded, making it inherently less safe.

- Depending on the oscillatory time period of fluctuations, fluctuating flow can lead to the same problems as low or excess flow, depending on the relative process system dynamics in response to heating or cooling, for example.

Hammer Blow--

The phenomenon of hammer blow, also referred to as "water hammer," is the propagation of a pressure shock wave through a liquid in a pipe line or other equipment. It occurs when flow is abruptly shut off. An example is when a control or solenoid valve is suddenly closed. It can also occur with manual valves, such as ball valves, that can be closed quickly. The pressure shock can be destructive to piping and other equipment in liquid-handling systems. The primary hazard is piping or equipment rupture that could directly or indirectly cause the release of a toxic chemical. A more insidious aspect of this phenomenon is that even if its effects are not immediately evident, its repeated occurrence may cause stress fatigue and eventual piping or equipment failure.

Three conditions that can lead to "water hammer" are (16):

- Hydraulic shock;

- Thermal shock; and

- Differential shock.

Hydraulic shock occurs when there is an abrupt interruption of flow. The conversion of the kinetic energy of the moving fluid to a physical pressure force is proportional to the square of the velocity, and the resulting pressure shock wave can be considerable. Hydraulic shock can occur from an abrupt valve closure, which includes check valves in pump systems when pumps are started or stopped. This phenomenon can be alleviated by providing a water hammer arrester in the line or by providing slower closing valves. Special consideration needs to be given to this effect when the line handles toxic materials directly, or in other process lines whose rupture could indirectly lead to a toxic release. This phenomenon must also be avoided in automated process systems where actuator action can cause abrupt valve closures. Manual systems may be less prone to this effect, but may not be entirely immune.

Thermal shock can occur when bubbles of vapor trapped in condensing liquids suddenly collapse, causing rapid liquid influx and shock waves to occur within the liquid. This can also occur in condensing two-phase systems where gas becomes entrapped between slugs of liquids. Each of these forms of hydraulic shock can damage equipment.

Differential shock can occur from two-phase flow in piping where the gas phase creates a plug of liquid from wave action, resulting in a high gas side pressure drop from the upstream to downstream side of the plug. The plug accelerates and gains enough momentum that when a change of direction is encountered, at an elbow for example, the inertia prevents the plug from changing direction as rapidly as the gas and a shock occurs. This shock can be great enough to cause damage to the piping.

2.3.2 Technology of Flow Control

The flow measurement and control system is intended to prevent flow deviation from leading to accidental releases. Initial process design or subsequent process modifications must provide for proper selection, implementation, and operation of these systems. Adequacy and reliability are the two evaluation criteria for these systems.

Measurement and Control--

Flowmeters are used for sensing and measuring fluid flow. A controller responds to this measurement and commands the final control element to appropriate action. The primary control element for fluid flow is the valve, actuated manually for manual control or through a mechanical actuator system for automatic control. The reliability of the fluid flow system depends on the reliability of the individual components.

A distinction is made between sensing and measurement elements. Sensing refers to detection; whereas measurement refers to converting flow sensing to a numerical quantity expressed in appropriate units of measurement. This is an important distinction when considering the appropriateness of various components in a flow measurement system, since different combinations of sensors and final measurement devices may encountered. Proper sensing and measurement of flow is the basis for controlling all other process variables: temperature, pressure, composition, and quantities.

The primary types of flow meters in common use in chemical process plants include the following:

- Differential static pressure;
- Momentum transfer (target, turbine, and positive displacement meters);
- Variable area displacement;
- Vortex shedding; and
- Magnetic field.

Each type of meter is more appropriate for some applications than others. For example, static pressure-based meters require small holes in either probes, flanges, or pipe walls, which can become clogged by solids. Such meters are obviously inappropriate when suspended solids are present in fluids. Improper selection of a flowmeter can lead to a process hazard.

The controller, responding to the information received from the flow measurement system, operates either a prime mover or a control valve. Flow control requires only proportional and integral controller action. The characteristic noise found in flow systems precludes derivative control action. A further characteristic of flow control is that there may be some transportation lag, but, in general, a flowing fluid responds quickly to the control action.

The final control element is usually the control valve. Sometimes, however, flow may be controlled indirectly by changing a pump setting or a gas pressure on a pressurized fluid feed tank.

Important criteria in the selection and operation of control valves include the proper size, trim, and action. Control valves and a pressurized feed tank system usually allow a quicker control response than a pump, with the exception, perhaps, of a complete shut off. This should be born in mind when evaluating flow control options for high-hazard systems. An automatic control valve should have a fail-safe action. It should fail appropriately open or shut in the event of a loss of electrical power or instrument air.

Emergency Trip Systems--

Flow switches may be used to sense either the initiation or cessation of fluid flow. These are primary devices in alarm and shutdown systems for chemical processes based on a flowing stream.

There are two categories of flow switches: variable-area devices and velocity-sensing devices (17). Low cost, simple switches based on both of these operating principles are available. These switches are suitable for applications where accurate settings are not required, such as lubricating-oil flow to rotating machinery.

More accurate switches may be required in critical applications, such as detecting flow deviations before a process is endangered. Here variable-area or rotameter type switches or orifice type differential pressure flow switches would be appropriate. Differential type switches can be direct acting or can transmit a pneumatic or electronic signal to the switch mechanism, alarms, or relays.

Variable-area switches have good rangeability, but usually cannot be used for flows as large as differential switches can handle. The latter are more limited at low flow ranges because of the square-root dependency of the signal or flow. They may become unreliable if the flow drops too rapidly below the maximum design flow. These types of switches are sensitive to the range selected for their application. Many other types of switches are available. For example, a pressure switch can be used as a flow switch by sensing pressure in a system when flow is present.

When integrated into a total emergency trip system, flow switches actuate valves and relays to close and open lines, and turn motors on and off. As will be discussed in other portions of this document, emergency systems controlling fluid flows are the basis for emergency control of pressure, temperature, quantity, and composition.

In general, exceeding the operating range of these types of switches may cause no permanent harm. However, where the reliability of the switch is really critical, the range must be selected with careful consideration of the likelihood of overrange service and the risk of harm caused by it. More details on the role of flow switches in process emergency control can be found in various literature sources (e.g., Reference 17).

Reverse Flow Prevention--

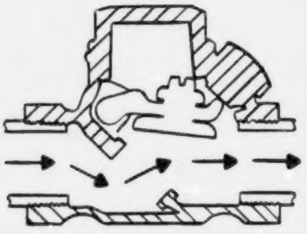
Reverse Flow prevention can be achieved by specific equipment, equipment configurations, and operational procedures. Equipment includes check-valves, sensing, automatic shutoff valves, and positive displacement pumps (rather than centrifugal pumps). Equipment configurations include relative elevation differences or traps between equipment items. Procedural approaches include direct shutoff with existing valves, or diversion of flow. The procedural methods depend on the sensing of and corrective response to reverse flow, and on previous provision for diversion in the design or construction of a facility.

The technological basis for reverse flow prevention is, therefore, the installation of the appropriate equipment. The most common device is the check valve. Various types of check valves are shown in Figure 2-3. Typical applications of the various types are given in Table 2-6 (18). While check valves provide some protection, they can fail by sticking open or not reseating properly. Sole reliance on check valves may be undesirable in critical service.

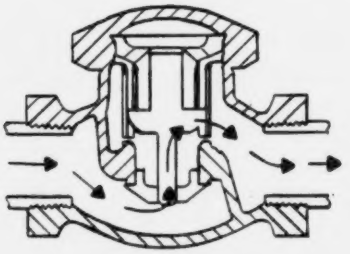
The principle of reverse flow prevention using positive displacement pumps is illustrated by comparison between a positive displacement pump and a centrifugal pump, as shown in Figure 2-4. Because the inherent clearances within a positive displacement pump are less than a centrifugal pump, reverse flow may be reduced when a positive displacement pump is not running. When it is running, an increase in upstream pressure is met by an increase in pumping head and maintenance of forward flow. In a centrifugal pump, the flow falls off sharply as upstream pressure increases and in extreme cases reverse flow can occur even if the pump is running. An idle centrifugal pump offers very little resistance to backflow.

Reverse flow is prevented through elevation differences when the feed vessel is sufficiently higher than the host vessel, ensuring that no condition in the host vessel would be sufficient to overcome the fluid head differential between the vessels.

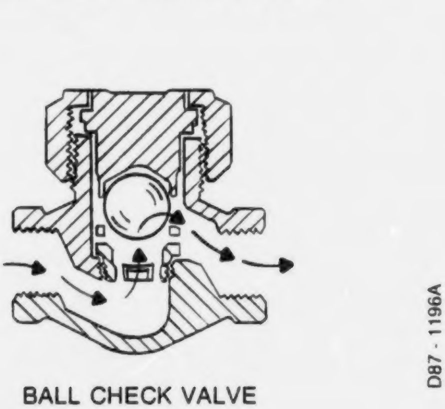
The trap principle of reverse flow prevention is based on interruption of flow with an intermediate vessel. During normal flow, the fluid is repumped for continued transport. Other arrangements may exist. The basic principle is interruption of stream continuity so that flow is not readily reversed.



SWING CHECK VALVE



HORIZONTAL LIFT CHECK VALVE



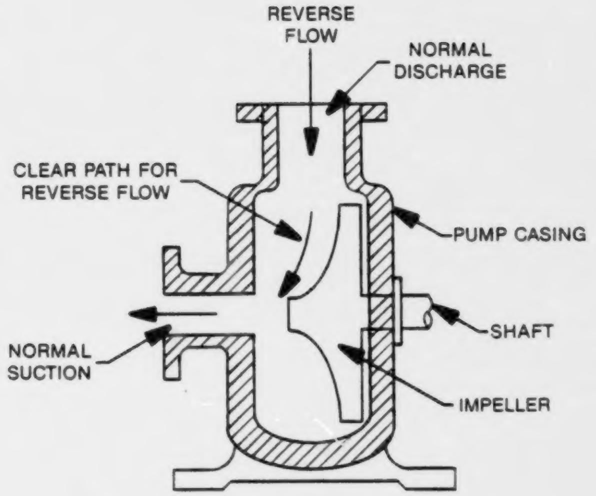
BALL CHECK VALVE

Figure 2-3. Check valve types.

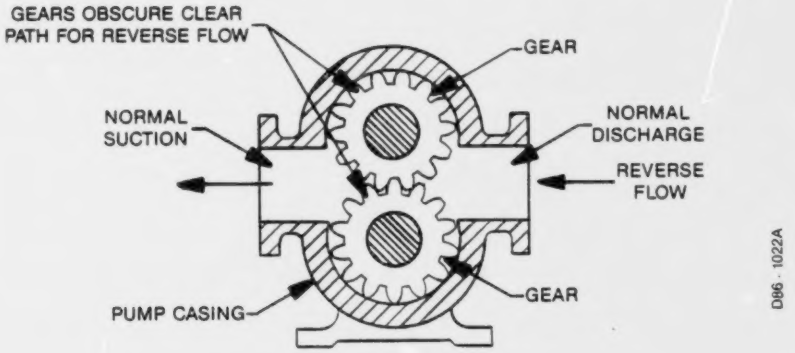
TABLE 2-6. TYPES OF CHECKVALVES

Type	Mechanism	Application	Limitations
		General: Prevent back-flow in lines.	
Swing check	Flow keeps swing gate open, while gravity and flow reversal close it. Tilting-type is pivoted at center and insures closing without slamming. Outside levers and weights are used on standard swing checks greater sensitivity for changes in flow is required.	Where minimum pressure drop is required-Best for liquids and for large line sizes.	Not suitable in line subject to pulsating flow. Some styles operate only in a horizontal position.
Piston check	Flow pattern as in globe valve. Flow forces piston up and reversal and gravity returns it to seat.	Good for vapors, steam, and water. Suitable for pulsating flow.	Many designs are for horizontal service only. Not common in sizes over 6 in. Not recommended for service which deposit solids.
Ball check	A lift-type check consisting of a ball with guides.	Stops flow reversal more rapidly than others. Good for viscous fluids which deposit solid residue that would impair operation of other types. Vertical or horizontal installation is possible.	Not common in sizes over 6 in. Not suitable for lines subject to pulsating flow.

Source: Adapted from Reference 18.


REVERSE FLOW
NORMAL DISCHARGE
CLEAR PATH FOR REVERSE FLOW
PUMP CASING
SHAFT
NORMAL SUCTION
IMPELLER

A. ILLUSTRATION OF REVERSE FLOW THROUGH CENTRIFUGAL PUMP


GEARS OBSCURE CLEAR PATH FOR REVERSE FLOW
GEAR
NORMAL SUCTION
NORMAL DISCHARGE
REVERSE FLOW
GEAR
PUMP CASING
D86-1022A

B. ILLUSTRATION OF PREVENTION OR REDUCTION OF REVERSE FLOW IN A GEAR PUMP

Figure 2-4. Examples of backflow through pumps.

Blockage Prevention--

Prevention of blockage means that any valves or pumps must be prevented from failing in a closed position when they should remain open. Lines, ports, and orifices must be kept clear of debris.

There are numerous potential sources of debris in chemical processes. Especially during startup especially, debris is present from pipe tape, ordinary dirt, welding drippings, corrosion scale, and the nuts, bolts, and other items inadvertently left in lines and equipment. Vigilance on the part of the startup personnel is the first defense against flow blockage occurring from such sources. Technological solutions include screens, strainers, filters, and traps.

When in-line screens, strainers, and filter devices are applied to prevent blockage, a secondary hazard is associated with the use of such devices; if not properly maintained they can become the source of blockage. The appropriateness of use must be evaluated on a case-by-case basis. Also, a filter can be provided with a bypass activated by a high upstream pressure on high pressure drop across the filter.

Two insidious causes of flow blockage are the buildup of corrosion products and the accumulation of polymer materials from the side reactions of various process fluids. Another is the attrition and breakage of solid materials in processes such as catalyst pellets and packing using in packed beds. Technological solutions here include the methods listed above, as well as changes in the characteristics of the solid materials used in the process.

Blockage or flow reduction is also a possibility under certain circumstances with slurries, high viscosity fluids, and melted materials at low temperatures. This can occur, for example, in coolers, or due to very low ambient temperatures. Solidification or buildup in slurries or freezing materials can reduce flow or cause complete blockage. The increase in viscosity can sharply reduce the flow rate for fluids.

Siphoning Prevention--

Siphoning can be prevented through proper design to ensure that if piping from a lower elevation to a higher elevation is submerged at the higher elevation end, appropriate steps have been taken to prevent backflow siphoning. Another technique is an interlock system wherein closure of a valve or cessation of pumping or failure of flow to stop will activate an alarm.

2.3.3 Control Effectiveness

The effectiveness of flow control is evaluated in terms of performance, limitations, and reliability. Proper selection is important to ensure that these criteria are met. Some guidelines for flowmeter selection are summarized in Table 2-7 (19).

The performance of individual components and complete systems depends on the interaction of physical and design choices made by the designer and fabricators. Sensors are limited by how sensitive they are to pressure and temperature beyond their design limits, and resistance to corrosion or erosion by process fluids. Controllers vary by type and individual vendor.

The effectiveness of emergency shutdown systems depends on individual components and on the overall system design. A key factor here is the response time required to achieve safe flow shutoff and the integrity of that shutoff.

Reverse flow prevention depends on the functioning of check valves and on the prevention of overpressurization of downstream vessels. Siphoning prevention relies on proper process design and construction and on other safeguards such as interlocks and alarms.

TABLE 2-7. FLOWMETER SELECTION GUIDE

Flowmeter Element	Recommended Service	Turn-Down Ratio	Typical Accuracy, Percent	Viscosity Effect	Relative Cost
Orifice	Clean, dirty liquids; some slurries	4 to 1	± 2 to ± 4 of full scale[2]	High	Low
Wedge	Slurries and viscous liquids	3 to 1	±0.5 to ±2 of full scale	Low	High
Venturi tube	Clean, dirty, and viscous liquids, some slurries	4 to 1	±1 of full scale	High	Medium
Flow nozzle	Clean and dirty liquids	4 to 1	±1 to ±2 of full scale	High	Medium
Pitot tube	Clean liquids	3 to 1	±3 to +5 of full scale	Low	Low
Elbow meter	Clean, dirty liquids, some slurries	3 to 1	±5 to ±10 of full scale	Low	Low
Target meter	Clean, dirty, viscous liquids, some slurries	10 to 1	±1 to ±5 of full scale	Medium	Medium
Variable area	Clean, dirty, viscous liquids	10 to 1	±1 to ±10 of full scale	Medium	Low
Positive Displacement	Clean, viscous liquids	10 to 1	±0.5 of rate	High	Medium

(Continued)

TABLE 2-7 (Continued)

Flowmeter Element	Recommended Service	Turn-Down Ratio	Typical Accuracy, Percent	Viscosity Effect	Relative Cost
Turbine	Clean, viscous liquids	20 to 1	±0.25 of rate	High	High
Vortex	Clean, dirty liquids	10 to 1	±1 of rate	Medium	High
Electro-magnetic	Clean, dirty, viscous conductive liquids and slurries	40 to 1	±0.5 of rate	None	High
Ultrasonic (Dobbler)	Dirty, viscous liquids and slurries	10 to 1	±5 of full scale	None	High
Ultrasonic (Time-of-travel)	Clean, viscous liquids	20 to 1	±1 to ±5 of full scale	None	High
Mass (Coriolis)	Clean, dirty, viscous liquids, some slurries	10 to 1	±0.4 of rate	None	High
Mass (Thermal)	Clean, dirty, viscous liquids, some slurries	10 to 1	±1 of full scale	None	High
Weir (V-Notch)	Clean, dirty liquids	100 to 1	±2 to ±5 of full scale	Very low	Medium
Flume (Parshall)	Clean, dirty liquids	50 to 1	±2 to ±5 of full scale	Very low	Medium

Source: Adapted from Reference 19.

Overfill protection relies on proper quantity measurement, as discussed in Section 2.6 of this manual, as well as an overall good flow control and proper shutoff.

The effectiveness of any system depends on its reliability. The fundamental elements of reliability include measurement, attenuation, and shutoff. The primary components of measurement are sensor and measurement devices. Attenuation is achieved by valve action, as is shutoff. System reliability depends on the reliability of the individual components and the system hardware and software. Software components include dead bands, dead time, and other dynamic response characteristics. And, as pointed out in the discussion on process control, the ultimate control of flow depends on the interaction of the control system with the process flow characteristics as much as on the characteristics of the control loop itself. Table 2-8 presents some typical reliability information on flow control components expressed as typical failure rates.

If a hazard evaluation discovers that the flow of specific streams is critical to preventing conditions that could lead to an accidental release, the entire flow sensing, measurement, and control system needs to be examined critically for its integrity. If necessary, the system needs to be modified to function more reliably.

2.3.4 Summary of Control Technologies

Table 2-9 summarizes major hazards or hazard categories associated with flow, and the corresponding control technology for both new and existing facilities. Numerous individual control technologies or procedural changes can be inferred for each category, based on the proceeding discussion of this section.

TABLE 2-8. TYPICAL FAILURE RATES OF FLOW CONTROL COMPONENTS

Component	Failure Rate Failures/Year
Flowmeters	
D/P cell and transmitter	0.76-1.73
Magnetic	2.18
Flow controller	0.29-0.38
Control valve	0.25-0.60
Flow switch	1.12
Flow indicators	0.026
Check valve (backflow prevention)	1.10×10^{-4}
Control loop	1.73

Source: Adapted from Reference 1.

TABLE 2-9. MAJOR HAZARD AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	New Facility	Existing Facility
Flow	• Low Flow - Blockage	• Flow, pressure, and temperature monitoring • Screening or filtration • Materials of construction • Equipment selection • Construction supervision • Design for polymerization inhibitors	• Add new flow, pressure, and temperature monitoring • Add screening or filtration • Change materials of construction • Change equipment type • Enhance maintenance • Add polymerization inhibitors
	- Vapor lock	• Design of temperature control system • Equipment selection	• Change temperature control system • Change equipment type • Change process chemistry
	- Cavitation	• Design of temperature control system • Equipment selection	• Change temperature control system • Change equipment type • Change process chemistry
	- Mechanical failure in prime mover	• Equipment selection	• Change equipment type

(Continued)

TABLE 2-9 (Continued)

Process Variable	Hazard	New Facility	Existing Facility
	- Leakage	• Equipment selection	• Change equipment type
	• Excess Flow	• Flow, pressure, and temperature monitoring • Flow limiters • Automatic flow shut-off trips • Emergency bypass diversion	• Add new flow, pressure, and temperature monitoring • Add flow limiters • Add automatic flow shut-off trips • Add emergency bypass diversion
	• Reverse Flow	• Check valves • Pressure control • Emergency bypass diversion • Equipment selection	• Add check valves • Add pressure control • Add emergency bypass diversion • Change equipment type
	• Fluctuating Flow	• Use pulsation dampeners • Process control system design • Equipment selection	• Add pulsation dampeners • Change process control system • Change equipment type
	• Hammer Blow	• System piping design • Equipment selection	• Change piping • Change equipment type

2.3.5 Costs

Both rough, order-of-magnitude capital and total annual costs of the various technological approaches to process modifications for flow have been estimated. Table 2-10 summarizes estimated costs.

2.3.6 Case Example (1)

A serious accident occurred at a plant where ethylene oxide and aqueous ammonia were reacted to produce ethanolamine. Ammonia backflowed in the ethylene oxide line, reaching the ethylene oxide storage tank. The ammonia went past several non-return valves in series, and past a positive displacement pump through a relief valve that discharged into the pump suction line. The ammonia reacted with 7,940 gal. of ethylene oxide in the storage tank, which ruptured violently. The resulting vapor exploded, causing widespread damage and destruction.

2.4 PRESSURE CONTROL

Pressure is the driving force for flow, and is therefore the driving force in any chemical release. Control of pressure is central to the prevention of accidental chemical releases. This section discusses pressure measurement and control considerations.

2.4.1 Pressure Hazards

Overpressure and underpressure can increase the probability of an accidental chemical release. Either can cause physical failure of process or storage equipment. Overpressure can cause the opening of a relief device, thereby allowing a toxic chemical to enter the environment. Potential consequences range from a small release of hazardous materials through leakage to a large, sudden release through the total and rapid failure of containment. Generally, overpressures are considered more hazardous than underpressures,

TABLE 2-10. COSTS OF COMPONENTS ASSOCIATED WITH PROCESS MODIFICATIONS FOR FLOW SYSTEMS

Basis: 4 inch diameter pipe line. Flow rate 250 gpm Pressure 50 psig.	Capital Cost Range ($)	Annual Cost Range ($/yr)	References
	(1986 Dollars)		
Flowmeter (D/P cell and transmitter, magnetic, and turbine)	2,500 - 5,100	380 - 780	5, 20, 21
Flow switch	-	-	21
Flow indicators	380 - 1,000	60 - 150	5, 20, 21, 22
Check valve	380 - 570	60 - 90	5, 20, 21, 22
Controllers			4, 24, 25
- Single loop, PID	800 - 1,600	69 - 138	
- Simple interactive, PID	$1,600 - 3,000	138 - 260	
- programmable, PID	2,000 - 6,000	173 - 519	
Control Valve	3,000 - 6,000	450 - 900	23, 26, 27
Control loop	6,000 - 12,000	900 - 1,800	Composite
- Conventional	3,000 - 15,000	260 - 1,298	

but process underpressure can also result in equipment failure by collapse or by causing leakage or backflow of incompatible materials. Process design or modification must include consideration of both over- and underpressure.

Structural failures caused by overpressure will often occur initially at a seal or joint and secondly in cracking or rupture of vessels, piping, and casings of other equipment (e.g., pumps). Potential sources of process leaks caused by overpressure include flanges, valve stems, pipe joints, welded or riveted vessel seams, and pump or compressor seals. Structural failures in vessel and pipe walls and equipment casings may occur as limited cracks or total failure.

A second, indirect group of hazards are process effects from pressure deviations from specified operating conditions. Since pressure is the driving force for flow, pressure deviations can lead to flow deviations with their attendant hazards, as discussed in Section 2.3 on Flow Control. Pressure also can affect process chemistry. Disturbances in pressure for a pressure sensitive process can sometimes result in the formation of unstable or incompatible by-products that could contribute to the pressure disturbance and result in overpressure and accidental release.

Initial process design and process modifications associated with pressure must consider all factors contributing to pressure deviations and loss of pressure control. These include process, equipment, and operating considerations.

Three related primary process events can lead to loss of pressure control: thermal expansion, excess material generation, and flow restriction.

Thermal expansion may be caused by a loss of temperature control or by excess heat due to a high reaction rate. Loss of temperature control may be caused by a malfunction in cooling and heating systems, or inadequate heat transfer due to inadequate mixing or fouling of heat transfer surfaces. Loss of reaction rate control may be caused by a loss of flow, temperature, composition control, or inadequate mixing.

Excess material generation may occur from runaway reactions or from uncontrolled flashing of liquids from sudden contact with high temperatures. If a reaction generates more moles of material than it consumes, then an accelerated reaction rate may generate enough excess material to result in an overpressure. Uncontrolled flashing could occur if a liquid were inappropriately introduced into a high temperature process.

Flow restrictions that occur as a result of fouling, freezing, valve closure, or other physical blockage may lead to an overpressure upstream of the restriction.

In many instances, the process failures listed above are caused by a mechanical failure in equipment. These failures may be the result of exceeding design capabilities, improper design, poor maintenance, defective equipment, fatigue failure, or corrosion.

Since not every form of mechanical failure can be prevented, insufficient design preparation to minimize the impact of mechanical failure can also be listed as a factor that contributes to loss of pressure control.

A loss of pressure control may occur as a result of fundamental design flaws, poor operating and maintenance practices, or insufficient operator training, especially in response to non-routine operating conditions.

2.4.2 Technology of Pressure Control

The pressure measurement and control system helps prevent accidental releases resulting from pressure deviation. Initial design or subsequent process modifications must provide for proper selection, implementation, and operation of these systems. Pressure relief for either excess over- or excess under-pressure is a fundamental aspect of pressure control.

Measurement and Control--

Pressure measurement relies on both sensing and final measurement devices. Control relies on how a system responds to pressure to take corrective action. Many types of pressure sensors and measuring devices are available, each having some unique feature in the mechanism it uses to sense and measure pressure. Probably the most common type of device in the process industries is the Bourdon gage, which is described in numerous texts and handbooks. A second category of devices is electronic. The most common type in this category is probably the strain gage sensor coupled with an appropriate signal conditioning and read-out instrument. The choice of device depends on the needs of the process and the operating environment. The actual pressure device must often be protected from direct contact with the process fluids. The device mechanism, combined with the method by which it is protected from process fluids or even external environments will determine the device's overall performance.

The pressure controller is the next device to be considered in a pressure control system. Details of these devices are discussed in numerous texts and handbooks in the general technical literature. Pressure control is achieved through control of the flow of a fluid (discussed in Section 2.3 on flow control).

Preventing the realization of pressure hazards requires the proper selection of pressure measurement and control equipment in both initial design and subsequent process modification. Proper selection must consider accuracy, precision, and reliability. A change in a pressure sensing and measurement element may be an appropriate process modification to enhance process safety.

Emergency Pressure Relief Systems--

An emergency pressure relief system is the final step in preventing overpressure or under pressure when the basic control system fails. Under certain circumstances a pressure relief system will be designed to vent directly to the atmosphere. This type of system is often used for emergency venting of explosions or where nonhazardous materials are involved. Its appropriateness where toxic materials are involved is debatable, unless an explosion or other effects of overpressure are a greater hazard. For toxic materials, a total containment system designed to capture and store the released material for later treatment and disposal, or to capture and treat the material as it is vented to render it "nonhazardous" before it is released, may be desirable. These systems are composed of a pressure relief device (a rupture disc, safety-relief valve or combinations), a vent header system, and a catch vessel or a final treatment device (usually a flare or a scrubber). The treatment devices are discussed in more detail elsewhere in this document; descriptions of the remaining components in a total containment system are presented below.

Rupture discs--A rupture or bursting disc is a non-reclosing pressure relief device composed of a pressure sensitive disk or membrane held in place by a support structure. A disc subject to reverse pressure may be fitted with an additional support designed to prevent reverse pressure rupture of the disc. A typical rupture disc arrangement is illustrated in Figure 2-5.

Types of rupture discs include domed discs, composite discs, reverse domed discs, and flat discs. Materials of construction include metal, plastics, resin-impregnated graphite or some combination of these. The rupture disc is frequently constructed with a corrosion- resistant coating or liner. A temperature shield such as an insulating flock may be installed upstream of the disc to protect it from high temperatures; however, this device would not be appropriate for rupture discs discharging into a downstream pipe or manifold system where constrictions would trap the flock material and cause a pressure venting discharge restriction.

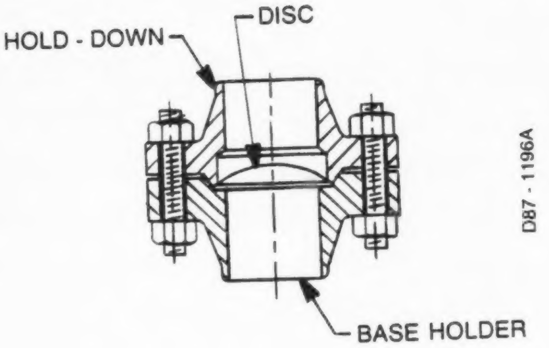

DISC
HOLD - DOWN
BASE HOLDER
D87 - 1196A

Figure 2-5. Typical rupture disc installation.

Discs may be piercing or non-piercing. A piercing disc has an assembly that contains a knife edge against which the disc presses as it ruptures to ensure a clean, complete, full-dimensional break.

Rupture discs may be used alone or upstream of a safety relief valve (discussed below). A rupture disc is often placed upstream of a relief valve to prevent leakage through a relief valve that may not reseat effectively, or to protect the valve against corrosion or even plugging from protracted polymerization of monomer vapors. This latter phenomenon has been known to occur.

Sizing and selecting a rupture disk should follow accepted design procedures, such as those recommended by the Design Institute for Emergency Relief (DIERS) of the American Institute of Chemical Engineers (AIChE), American Petroleum Institute (API) or the American Society of Mechanical Engineers (ASME). A new set of standards that is a fairly comprehensive guide for both manufacturers and users of bursting disks has been assembled in Great Britain. An overview of rupture disks with numerous references is presented in a comprehensive book on loss prevention by Lees (1).

The Design Institute for Emergency Relief Systems (DIERS) has assembled a manual and a computer program package useful to a safety-relief system specialist; however it is not geared toward the novice. This document is particularly important when considering the effect of two-phase, vapor-liquid flow on the sizing of a relief device. Two-phase flow occurs when a pressurized vessel that contains liquid is rapidly depressurized. The occurrence of two-phase flow during emergency relief almost always requires a larger relief system (two to ten times the area), compared to that required by vapor venting. Some of the information generated by DIERS has been used by Fauske to develop a nomograph for sizing an emergency relief device (28).

Safety-relief valves--The term "pressure relief valve" is a generic term applied to various types of valves used to relieve pressure. API RP 520 gives additional definitions within the safety relief valve category (30). A safety valve is characterized by rapid full opening, or pop action, and is normally used for steam, air, gases, or vapors. Relief valves are used primarily for liquid service and are characterized by valve openings proportional to the rise in pressure over the opening pressure. A safety-relief valve can be used for either liquid, vapor or gas service. In practice, the terms safety valve, relief valve, and safety-relief valve are often used interchangeably.

A conventional safety-relief valve is illustrated in Figure 2-6. For this device, the bonnet (as shown in the diagram) may be vented either to the atmosphere or to the discharge side of the valve. Backpressure will decrease the set pressure for a valve with a bonnet vented to the atmosphere and will increase the set pressure for a valve with a bonnet vented to the discharge side of the valve. To compensate for the effects of backpressure, a balanced safety-relief valve may be used. For this type of valve, backpressure in the discharge line will have very little effect on the set pressure of the valve. The balanced safety-relief valve is often the most appropriate type of valve for a total containment system.

A final type of valve is the pilot-operated safety-relief valve, which is designed to achieve good mixing of the substance being discharged and air. A pilot-operated safety valve is often used when a flammable material must be diluted below its flammable limit with air before it can be safely released.

The API, ASME, and the National Fire Protection Association (NFPA) have each issued guidelines and standards for the sizing and installation of safety-relief valves (29,30,31). Criteria for sizing include fire exposure, fill rates, thermal expansion, and reaction/decomposition venting. DIERS manual also applies to safety relief valves. William A. Scully has prepared a brief discussion of some of the common malfunctions of safety-relief valves and how these malfunctions can be corrected (32). D.M. Papa discusses the effects of back pressure on a safety relief valve (33). The pitfalls of

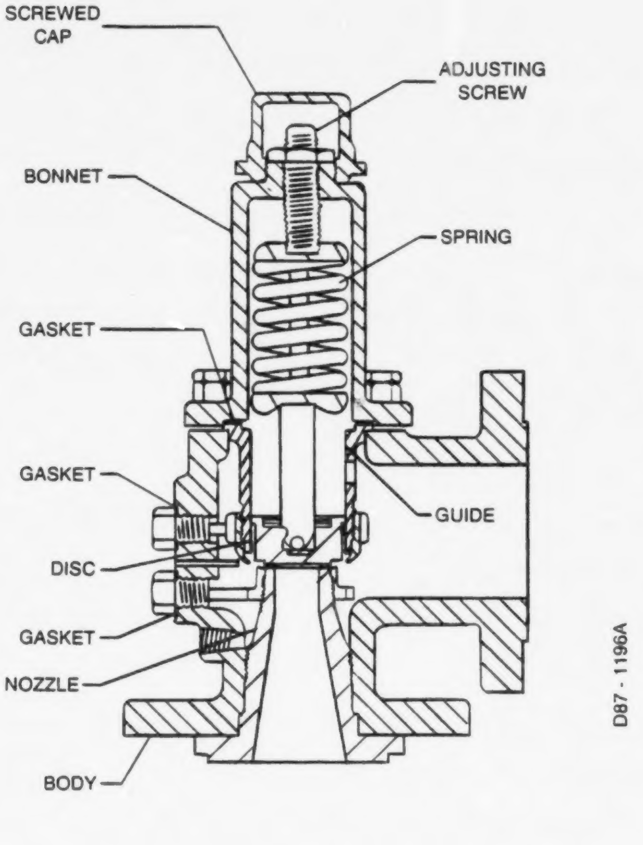

SCREWED CAP
ADJUSTING SCREW
BONNET
SPRING
GASKET
GASKET
GUIDE
DISC
GASKET
NOZZLE
BODY
D87 - 1196A

Figure 2-6. Cross-section of a typical pressure relief valve.

sizing a relief valve when the equipment (specifically, a distillation column) will be used for more than one process is discussed by Bradford et. al. (34). An overview of pressure relief valves, with numerous additional references, is presented by Lees (1).

An important consideration in relief valve installations is to keep them from being isolatable while still providing for their maintenance while a process unit is on-line. A twin-valve configuration with a two-way, three-port block valve, which blocks only one relief valve at a time, is desirable. When a standard block-valve is used upstream of either a single or two relief valves, it should be locked or sealed open to prevent unintentional or unauthorized closure.

Vent headers--The vent header is the pipework that delivers material from the discharge side of the relief device to a point where it can be rendered nonhazardous. These systems are often complex, having several relief devices using one common header system. For toxic materials, it might be well to consider addition of a header to the relief device system that leads to some form of secondary containment or treatment. However, depending on the situation, even with a toxic material, a discharge directly to the atmosphere still might be a safer condition than risking a restricted relief discharge. The appropriate configuration must be evaluated case by case.

Sizing the vent header for an emergency relief system is not a simple matter. For safety, the system must be sized to accommodate more than the flow from the largest single source. For economy, the system must usually be sized for some flow less than the sum of all sources. In approach presented by Fitt, overpressure due to fire, electrical power failure, instrument air failure and cooling water failure are considered (35). Fitt calculates the effect of each of these failures for three different time periods and sizes the pressure relief header for the maximum load that results from failure of one of the items. A method for sizing relief headers is also given in API RP 520 (29).

Pressure trip systems--A pressure trip system may be used instead of an emergency relief system. A pressure sensor activates a switch when the pressure is approaching an unacceptable level. The switch then shuts a valve to isolate a part of a process from the source of pressure. As an example, a pressure switch in downstream equipment may stop the flow of steam to a feed preheater or to a distillation column reboiler.

Because of the limitations discussed for relief systems, a pressure trip system should be several times more reliable than a pressure relief valve for the same application. Calculation of this reliability should be based on the calculated proportion of the time for which a system will be in the failed state, referred to as the fractional dead time. This method considers both the fault-rate of the individual components and the frequency of proof testing.

2.4.3 Control Effectiveness

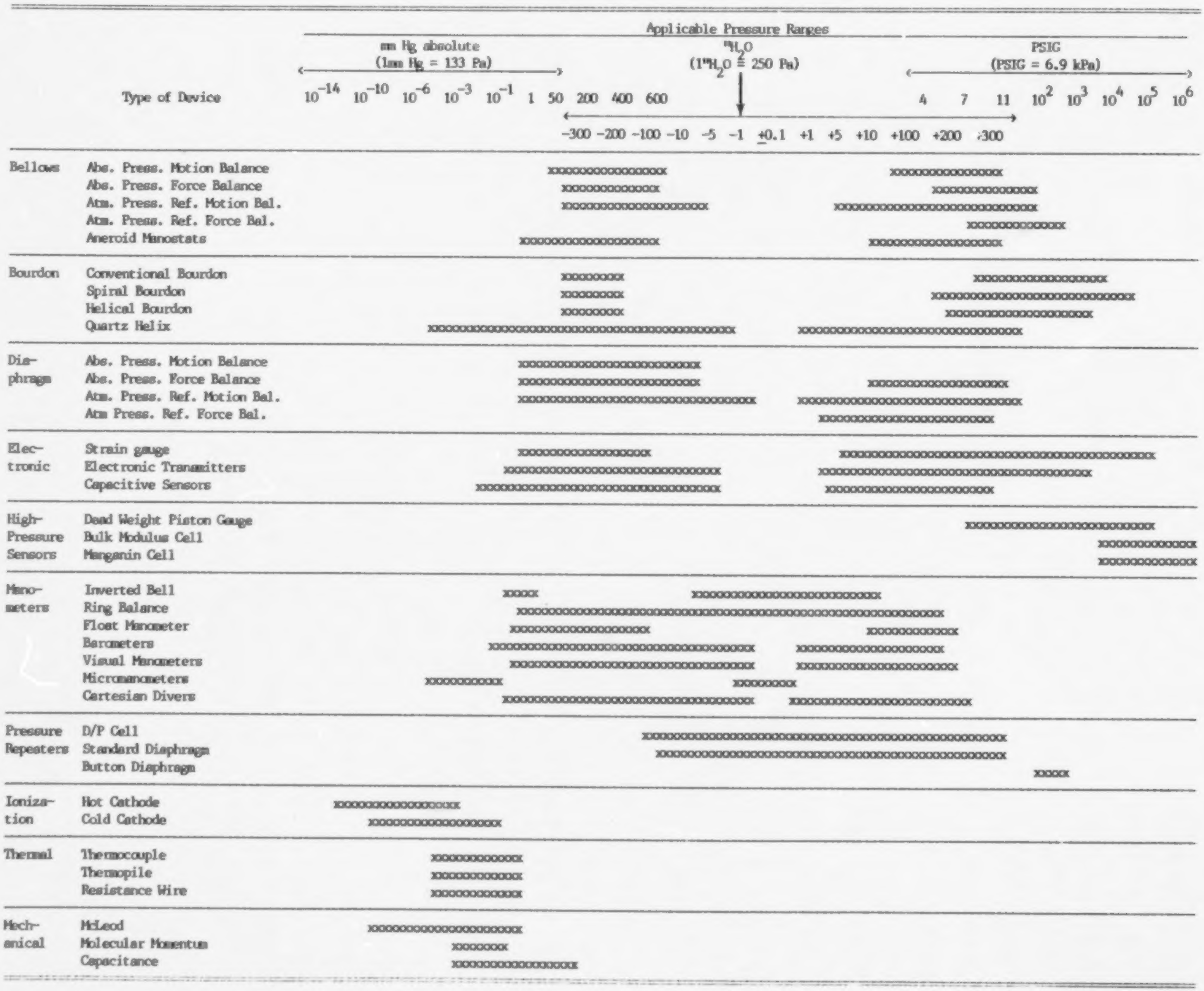
The control effectiveness of pressure control is evaluated in terms of performance, limitations, and reliability.

Measurement and Control--

Table 2-11 lists a variety of pressure sensing and measurement devices and pressure ranges over which they may be used. In addition to a pressure range, each device has a variety of other performance limitations, including acceptable sensitivity, operating temperatures, reproducibility, and materials of construction. The range of values for these parameters is quite large and a device is routinely available for almost every temperature, pressure range, and operating environment likely to be encountered in typical chemical processing applications.

Because of the large number of choices, care must be taken to select an appropriate device for each application. Each pressure device can only be expected to perform satisfactorily within its design specifications. The

TABLE 2-11. PRESSURE SENSING AND MEASURING DEVICES



Source: Adapted from Reference 19.

degree to which a device can withstand excursions beyond its operating range varies. Some sensors may be permanently damaged by even brief excursions out of their operating range. The sensitivity of devices to such excursions should be taken into account during initial design or subsequent modifications.

Because there may be no external indication that a pressure device is giving an incorrect reading, redundancy of pressure sensing and measurement should be used in all critical processes. For example, a common failure in a Bourdon gage is to jam at some false reading. It may be advisable to use two different types of devices if the potential cause of device failure is sensitivity to process pressure excursions. An appropriate solution might be to use a cruder, more robust type of device to roughly indicate the pressure as a back-up for the more sensitive sensor actually used for process control.

Information on the reliability of a specific device can be supplied by the vendor, although this information may not itself be reliable and must be used with caution. A number of statistics on reliability have been assembled, some of which are presented later in this section.

Emergency Pressure Relief Systems--

Rupture discs--A rupture disc is generally preferred over a relief valve when pressure rise may be so rapid as to virtually constitute an explosion, when even minor leakage cannot be tolerated, or when the potential for corrosion and/or blockage would limit the effectiveness of a valve.

The set pressure for a rupture disc is usually specified by a range, that can vary anywhere from +/-2% to +/-25% of the mean bursting pressure (34).

The reliability of rupture discs varies with type. The simplest form is a flat disc made of a material weaker than the vessel it is designed to protect. Because it is virtually impossible to accurately predict the bursting pressure for this type of disk, a large margin is required between the operating pressure and the bursting pressure. An exception is the brittle bursting disc, often made of resin-impregnated graphite, which is often used for low pressure and corrosive applications.

Several types of domed discs are available. One variety is a thin piece of dome-shaped metal. Because they are very thin, their bursting characteristics are altered by even slight corrosion, elevated temperatures, or minor deformations of the surface. Pressure fluctuations near the set pressure of these discs can result in premature rupture as a result of fatigue. Generally these discs cannot be operated above 70% of their rated bursting pressure, and even less at elevated temperatures (28). They will collapse under a comparatively small back pressure and are generally installed with a backpressure support. An improvement in domed design is a disc made of thicker material radially scored to purposely weaken the surface. Because most of the disc is made of heavier material, it is less susceptible to fatigue. These discs can generally be operated at up to 80% of their design burst pressure (1).

The inverted domed disc has advantages over either of the domed disks described above. One variety is composed of an inverted dome with a knife edge or some other variety of puncturing device positioned next to the disc. When the bursting pressure is reached, the dome inverts and is punctured. Another variety is so constructed that when the disk inverts it pops free of its support and is caught immediately downstream. Both smooth and scored surface inverted dome disks are available. The danger with inverted domed discs, however, is that the disc may not be punctured when it inverts. These discs can operate at pressures up to 90% of their design capacity and can be manufactured to relieve within 2% to 5% of their design capacity (35).

Rupture discs are potentially hazardous because they are nonresealable and they provide total depressurization. A rupture disc gives no external indication that it has blown. Once a disc has blown, the vessel it was protecting is no longer isolated from whatever else may be present in the containment system, and it is possible for material to backflow into the vessel from the containment system. This would be hazardous if the materials were incompatible. Vessels normally at atmospheric pressure are particularly susceptible to this since a loss of pressure from the vessel would not indicate a ruptured disc. An undetected ruptured disc in an atmospheric vessel could result from a previous overpressure, damage during installation, or corrosion.

Because a rupture disc provides sudden, total pressure relief, it may result in two-phase, vapor-liquid flow from a pressurized vessel when liquid is initially present. This may be hazardous if the disk or the containment system downstream is not sized for such a release. Flares and scrubbers for these types of systems are not usually designed to handle the large quantities of liquid that could be released. Any incompatibilities between the liquid released and the materials within a downstream containment system might be quite serious because of the quantity of liquid that could be present. A knockout vessel of some type is needed when a two-phase release is possible. In such cases, and when a heated material whose melting point is above ambient temperature is involved (such as molten sulfur), particular care must be taken. Lines leading up to, and including the catch vessel must be heated to prevent plugging when the liquid cools.

A seemingly trivial, but actually very dangerous hazard associated with the use of rupture discs is that they can be easily installed upside down. The consequences of installing a disk upside down will depend on the type of disc, but in most cases the device will relieve at a substantially higher pressure than intended. All disks should have a tag indicating the proper direction for installation; these tags should be regularly inspected.

Other disadvantages of rupture discs are that once installed they cannot be non-destructively tested, wrong discs can be installed, and multiple discs nested together can be installed. Avoidance of these latter two occurrences requires strict adherence to proper, installer training and auditing procedures.

Safety-relief valves--A properly designed safety-relief valve will: 1) open automatically at a pre-adjusted set pressure using the energy of the fluid, 2) open fully to its rated flow capacity at a pressure typically not more than 10% above the set pressure, 3) shut flow off completely when the pressure falls to a preset reseat pressure (minimally between 3% to 5% below the set pressure).

Both undersizing and oversizing a valve can impair its effectiveness. Undersizing a valve presents the obvious hazard of not being able to relieve pressure fast enough. An oversize valve may chatter (rapid opening and closing), resulting in excessive wear or damage to the valve. An oversized valve may reseat improperly, resulting in leakage into or out of the vessel.

It is common to place a safety-relief valve downstream of a rupture disc. The rupture disc will prevent minor leakage of process materials and the safety-relief valve will allow the process to be resealed when the pressure drops. Sometimes a rupture disk of corrosion-resistant materials is used to protect a safety-relief valve made out of less exotic materials and expensive materials. Care must be taken to ensure that the presence of the blown rupture disk does not affect the anticipated performance of the safety-relief valve.

The dangers associated with pressure-relief valves are the possibility of isolation with shutoff valves either upstream or downstream, two-phase flow through the valve, and the potential for failure of the valve because of human error or mechanical failure. Another hazard is having other foulable fittings (e.g. check valves, flame arresters) between a relief valve and a vessel or between a relief valve and safe discharge. These can also cause isolation.

Since the safety-relief valve will reseat when the pressure drops, the potential for two-phase flow is not as high as it is with a rupture disk. However, two-phase flow is possible while the valve is open and rapid release is occurring. In the case of a runaway reaction, a large portion of the vessel contents may empty before the pressure falls below the reseating pressure. As with a rupture disc, a safety-relief valve will be grossly undersized for a two-phase release if it was sized taking only the vapor release into account. Much research has been and continues to be conducted in this area by the Design Institute for Emergency Relief Systems (DIERS).

Human error can result in the failure of a safety-relief valve in several ways. Unlike a rupture disk, a safety-relief valve has internal settings that can be adjusted to alter the performance of the valve. Incorrect adjustment of these settings during installation or routine maintenance could increase the potential for overpressure. The physical orientation of the valve is important during installation. A valve should be installed vertically, or if a type is designed for such service horizontally, with the discharge pointing down. In addition, the valve should not be required to support the weight of the discharge piping.

The hazards associated with any valve are the same with a safety-relief valve. Seals may leak, the valve may plug, or corrosion and abrasion may destroy the integrity of the valve. These hazards may be more pronounced for a safety-relief valve since it may go for very long periods of time without being called into service. For this reason, regular inspection and testing of the valve is essential to ensure its proper function when required.

If a safety-relief valve is located downstream of a rupture disc, then a pressure-detecting device should be placed in the line between the disc and valve. A premature failure of the rupture disk would otherwise go undetected and the safety-relief valve would be exposed to the conditions the rupture disc was installed to prevent. Also, since the disc relies on a differential pressure to rupture, a leak could reduce this differential and cause the pressure to rise well above the set pressure before the disk gave way.

Vent header--The effectiveness of a vent header depends on its proper sizing. The primary danger with vent headers in a total containment system for pressure relief discharges is that the vent header may not be sized to accommodate a worst-case event of simultaneous discharge of all or several relief valves connected to the header system. A second hazard is the potential for mixing incompatible materials in the vent header system or cross-contaminating the contents of one vessel with material vented from another vessel.

Pressure trip systems--

A trip system may be preferable to sole reliance on a pressure relief system when a toxic material is involved. Because of its mode of operation, no hazardous materials are discharged in the event of an overpressure. If properly applied, a pressure trip system may be more reliable than a pressure relief system. However, the system has no backup if not used in conjunction with pressure relief. If a safety-relief valve fails to open at its set pressure, it may open at some higher pressure before the structural limits of the equipment it is protecting are reached. A pressure trip system can never substitute for a pressure-relief valve installed to protect against overpressure due to fire.

The reliability of a trip system is a design criterion. Generally, a pressure trip system is designed to be at least ten times as reliable as the pressure relief valve it is intended to complement.

The reliability of a pressure trip system can be improved by a variety of methods that may be used to improve the reliability of any control system. Individual system components may be replaced with more reliable (and usually more expensive) components. Redundancy of hardware and software in various forms of backup systems may be used.

For critical applications a combined system may be configured as follows:

- First line of prevention - pressure control loop;
- Second line of prevention - pressure trip system; and
- Third line of prevention - relief valve discharging to header with protection technology system (e.g., scrubber).

The pressure for activating the system increases at each step.

Reliability of Pressure Control Components--

The reliability of pressure control depends on the reliability of the individual components that comprise the pressure control system. The reliability of a full multicomponent control system also depends on the architecture of the specific system. Table 2-12 presents reliability data for some individual components.

2.4.4 Summary of Control Technologies

For both new and existing facilities, Table 2-13 summarizes major hazards or hazard categories associated with pressure and the corresponding control technology or procedural categories. Numerous individual control technologies or procedural changes can be inferred for each category based on the preceding discussions of this section.

2.4.5 Costs

Table 2-14 presents the costs of components associated with process alternatives for pressure measurement and control systems. This table presents a list and costs of typical components. There are many individual variations of these component groupings, since other possible components are not included here. These costs give an order-of-magnitude basis for

TABLE 2-12. TYPICAL FAILURE RATES OF PRESSURE CONTROL COMPONENTS

Component	Failure Rate Failures/year
Pressure Transducer/Transmitter	0.76-1.73
Pressure Indicator	0.026-1.41
Pressure Switch	0.34
Control Valve	0.25-0.60
Pressure Controller	0.29-0.38
Pressure Control Loop	1.73

Source: Adapted from References 2,8,19,37.

TABLE 2-13. MAJOR HAZARD AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	New Facility	Existing Facility
Pressure	Overpressure	• Flow, pressure, and temperature control system design • Emergency trip system for flow shutoff or automatic venting • Design to avoid flow blockage • Provide pressure relief for thermal expansion • Provide general pressure relief	• Change flow, pressure, or temperature control system • Add emergency trip system for automatic flow shutoff or automatic venting • Change system to avoid flow blockage • Add pressure relief for thermal expansion • Add or change pressure relief system
	Underpressure	• Flow, pressure, and temperature control system design • Emergency trip system for flow shutoff or automatic vacuum break • Mechanical vacuum breaker	• Change flow, pressure, or temperature control system • Add emergency trip system for automatic flow shut off or automatic vacuum break • Add mechanical vacuum break
	Fluctuating Pressure	• Control system design • Equipment selection	• Change control system design • Change equipment type

TABLE 2-14. COSTS OF COMPONENTS ASSOCIATED WITH PROCESS MODIFICATIONS FOR PRESSURE MEASUREMENT AND CONTROL SYSTEMS

Basis: 4 inch diameter piping. Pressure range 0-300 psig	Capital Cost Range ($) (1986 Dollars)	Annual Cost Range ($/yr) (1986 Dollars)	References
General purpose pressure transducer	200-500	33-81	40
Indicators	200-600	33-99	40
Computer interface system	2,000	330	40
Pressure gauge	50-250	8-43	40
Control valve	3,000-6,000	450-900	3,20,21
Controller	2,000	326	24,25,26,27
- conventional	6,000-12,000	910-1,800	
- via process control computer	3,000-15,000	260-1,298	
Control loop			Composite
- simple, single loop, PID	800-1,600	69-138	
- simple, interactive, PID	1,600-3,000	138-260	
- programmable, PID	2,000-6,000	173-519	
Rupture disks	150-225	28-42	20,23,28
Relief valves	7,000-12,000	609-952	20,23,27

estimating costs of process modifications involving the pressure measurement and control system.

2.4.6 Case Examples (1)

An explosion occurred in a vinyl chloride pump on the "recovered" vinyl-chloride monomer system (RVCM), seriously injuring an operator. The line sections before and after the pump had been removed and the explosion occurred in the idle vented pump about an hour later. Investigation showed that the entire RVCM system was contaminated with vinyl chloride polyperoxide, an unstable material. There had been earlier abnormal occurrences where the RVCM gas compressors had not shut down at low pressure because a pressure switch had failed. RVCM liquid had accumulated in the storage tanks for 20 days and the acidity level in the vinyl chloride feed had been high.

A failure of the control system in a chlorine cellroom caused a back-pressure to develop. When operating personnel tried to shut the system down manually, failure of these controls caused a serious chlorine release. One of two compressors taking hydrogen from a low pressure gasholder continued to operate and failure of a low level trip created a negative pressure, allowing air to leak in and cause an explosion in the compressor cooling coils. The hydrogen/air mixture in the holder diffused into the catalyst purification unit, a high temperature developed, and another explosion occurred. The gasholder trip did not operate because the timer was bypassed by a "jumper".

2.5 TEMPERATURE CONTROL

Like flow and pressure, temperature is one of the primary variables in a chemical process. The temperature of a system strongly influences which chemical reactions are preferred and the rate at which they occur. Phase changes are determined by temperature. The volume of gases, and to some extent liquids, depends on temperature. For these reasons, a loss of pressure control, discussed in the preceding section, will often be the result of a loss of temperature control. The inability to control temperature can therefore indirectly or directly lead to conditions that cause an accidental release. Proper design of a temperature measurement and control system is therefore essential to preventing accidental releases.

2.5.1 Temperature Hazards

For some chemical reactions a loss of temperature control may result in a runaway reaction with excess generation of heat and materials that could lead to an overpressure and an accidental release.

A chemical reaction system will generally have a specified temperature range in which it must operate to successfully produce the desired product. This range is usually set by balancing reaction rates with economics to achieve an acceptable reaction rate for the primary reaction, while minimizing competing reaction rates, the size of reaction vessels, and heating and cooling systems. The consequences of operating above or below the set operating temperature will be a function of the specific reaction system.

High temperatures are usually more hazardous than low temperatures, but both must be considered in evaluating temperature's contribution to process hazards. Often a low temperature will slow down or quench the reaction. This may be hazardous if an unreacted feed stream is incompatible with downstream operations. High temperatures may result in a number of undesirable consequences. At higher temperatures, reaction rates are likely to increase, resulting in excess heat and material generation that may lead to an overpressure. A high temperature may result in the formation of unwanted by-products because of thermal decomposition of the product or increased reaction rates for competing reactions. Thermal decomposition often results in the generation of more moles of material than are consumed; this could result in an overpressure. The consequences of unwanted by-product formation due to the competing reactions will depend on the nature of the by-products formed. The presence of lighter molecular weight by-products would result in an increased system pressure and could result in an overpressure. A reaction may form by-products that react with downstream materials or that are corrosive to the materials of construction. Both of these events could contribute to the potential for an accidental release.

Increases in temperature result in thermal expansion, which can result in increase in pressure and an accidental release. A loss of temperature control in any process involving heating or cooling may lead to an accidental release. Two-phase processes are more sensitive to temperature fluctuations than single-phase processes. Gas phase processes are more sensitive to temperature fluctuations than liquid phase processes. However, thermal expansion can be very destructive in a sealed liquid-full system; a system with no vapor space. Sometimes heating or cooling results in a phase change: freezing, condensing or vaporization. Phase changes may lead to overpressure or underpressure. The expansion of water on freezing is an example of one consequence of cold temperature.

Most physical properties vary with temperature. The performance of any physical operation will be affected. The consequences of a temperature fluctuation must be evaluated on a case-by-case basis. Sometimes a loss of heat to a stream will decrease the solubility of a component in the stream to the point where it drops out of solution. Solidified material could clog lines and would affect the chemical properties of the stream; this could ultimately lead to an overpressure and an accidental release. Partition coefficients are temperature dependent and processes such as liquid-liquid extractions will not function properly as temperatures vary.

A loss of temperature control may lead to an accidental release due to material failure. Structural or sealing materials lose physical strength as the temperatures increases. At an elevated temperature, a construction material may stretch, bend or crack under load conditions that were acceptable at lower temperatures. Metals experience fatigue if subjected to repeated heating and cooling. This can lead to eventual failure under previously acceptable conditions. Plastic linings used to protect metals from corrosion may fail at excessive temperatures. Expansion joints are often more sensitive to high temperatures than other process piping and may fail if temperatures are elevated above design specifications. Extremely cold temperatures may result in brittle failure of metals, especially if the metal is subjected to high stress under these conditions. Rapid changes in temperature can also be destructive.

A hazard in heat transfer equipment is the possibility of accidental mixing of a heat transfer fluid with a process fluid. Heating and cooling are usually accomplished via heat exchangers or various forms of jacketed equipment. A leak may develop in a vessel or pipe wall that allows the jacket fluid to enter the vessel, or vice versa, depending on which pressure is higher. A special danger arises when the process side is at a higher pressure than the jacket side. The process side of a jacket of a vessel frequently has a pressure rating higher than the jacket. A leak could cause high pressure process material to rupture the jacket or exit through the jacket's relief valve. If the jacket is at a higher pressure than the process, then the heat transfer fluid will contaminate the process, which could result in an accidental release if the heat transfer material is incompatible with the process materials.

Flashing may occur when a hot liquid with a high boiling point is mixed with a lower boiling point liquid. This flashing may result in a rapid overpressure. The accidental mixing of a heat transfer fluid with a process fluid, as was discussed above, may sometimes be the cause of such an event. A number of accidents have occurred when a hot oil is transferred to a tank that has been steam cleaned and not thoroughly cleared of condensation. The condensate has flashed and resulted in an overpressure.

Process temperature control is closely related to flow control. Reaction rates and the heat generated by a reaction is often governed by flow control. The rate of heat transfer depends on the flow rate of a heating or cooling medium. Therefore, a loss of a flow control can often result in a loss of temperature control.

Process Considerations--

A process-related loss of temperature measurement and control occurs when the temperature measurement and control systems are functioning according to design standards but the heat generated by the process exceeds the capacity of the cooling system.

Chemical reactions either generate or require heat. Anything in a chemical reaction system that alters the rate of reaction alters the rate of heat generation and/or consumption and affects the ability to control temperature. As an example, loss of flow control of a reactant to an exothermic reaction may result in the generation of excess heat. If the heat generation rate exceeds the ability of the temperature control system to remove it, the result is a loss of temperature control.

Failure to achieve proper mixing may result in a loss of temperature measurement and control. Improper mixing of reactants may result in localized hot spots. In a jacketed process vessel, for example, if there is poor mixing then there will be very poor heat transfer between the jacket and the reactor contents. Temperature measuring probes will not measure a representative bulk temperature when there is inadequate mixing.

Equipment Considerations--

A failure of flow control may cause a failure of temperature control. As mentioned above, in most cases, temperature control is achieved through control of the flow of either the process materials or of a heat transfer fluid. In some cases heating is accomplished by direct heating with gas, oil, or electric heating elements. These are often used to heat a hot oil, steam, or some other heating fluid; thus flow control is still the ultimate method for heat transfer and temperature control.

As discussed above, a leak in the wall that divides process materials from heat transfer fluids will sometimes result in an accidental release. This is particularly a problem because these surfaces have fluid on each side and are therefore difficult to inspect for signs of erosion, corrosion, or defect.

Since not every form of mechanical failure can be prevented, insufficient design preparation to minimize the impact of mechanical failure can also be listed as a factor contributing to loss of temperature measurement and control.

Operating Considerations--

A temperature control system will only be as accurate as the standard to which the measuring devices are calibrated; therefore, improper calibration or maintenance of the system can contribute to failure in the control system.

A lack of chemical and thermodynamic data will contribute to the potential for a loss of temperature control. To design a proper control system, plant engineers should have a sufficient understanding of the consequences of temperature excursions. Operators should have training sufficient to respond to deviations in normal operating conditions. Often plant personnel do not know what side reactions could occur at various temperatures and do not have enough information to quantify the temperature dependence of all the reaction rates. This detailed information is often lost with the transfer of information between research and development, or it was never obtained in the rush to commercialize a new process. A total understanding of a complex chemical process may not be possible, but a lack of chemical and thermodynamic data will always leave plant management in the position of viewing temperature control as a mystery.

2.5.2 Technology of Temperature Control

The first line of prevention of an accidental release as a result of a loss of temperature control is the temperature measurement and control system. Process modifications must consider the capacity and reliability of these systems. The second line of prevention is a temperature trip system designed to regain control of the process once temperature control has been lost. The ability to design a system that will adequately control temperature will depend on the chemical and thermodynamic data available; adequate data will potentially lead to better design.

Measurement and Control--

Temperature measurement relies on both sensing and final measurement devices. Control relies on the corrective actions that a system takes in response to changes in temperature. A variety of temperature sensors and measuring devices are available. Each variety has some unique feature in the mechanism it uses to sense and measure temperature. Temperature measuring devices organize the output of the temperature sensing device and/or convert the output to a meaningful temperature readout.

Several commonly used temperature sensing devices are discussed below. Additional discussions on a wide variety of temperature sensing devices may be found in numerous sources (e.g., Reference 39). Common varieties of temperature sensing devices used in the process industries include: thermal expansion devices, thermocouples, thermistors, resistance thermometers, and a variety of solid state sensors.

One group of temperature sensing devices rely on thermal expansion of materials, usually metals. The thermal expansion of these devices is often linear with temperature, making an additional temperature measuring device unnecessary. Additionally, the output from these devices is visual and they are generally not used for remote sensing. Bimetallic thermometers, filled thermal elements, and glass stem thermometers are types of temperature sensing devices that rely on thermal expansion to measure temperature. These devices are common in older plants or in situations where a rugged local backup to an electronic temperature sensing device is desirable.

A thermocouple is a simple temperature device composed of two homogeneous wires of dissimilar metallic composition joined at one end to form a measuring junction and at the other end to a measuring device. The measuring device provides an internal connection between the two wires so that they form a closed path through which current may flow. When heat is applied to the junction of the two dissimilar metals, a small electromotive force (emf) is generated and current flows through the thermocouple loop. In commercially available thermocouples the emf is linearly proportional to the temperature at the measuring junction. Thermocouples are rugged and inexpensive. They are best suited for applications where moderate accuracy over a wide temperature range is required and are very common in the chemical process industry.

Thermistors are a form of solid-state sensor that use a ceramic semiconductor which measures the change in the resistance of the semiconductor as temperature varies. The resistance is nonlinear and must be converted to a linear temperature scale by a temperature measuring device. Thermistors are usually best-suited for applications where accuracy and rapid response are required over a narrow temperature range; they tend not to be as well-suited for measuring temperatures over a wide range.

A resistance thermometer is a device that uses the change in resistance and temperature of a conductor to measure temperature. These devices have conductors made of platinum, nickel, or a nickel/iron mix. They are accurate and are available over a fairly wide temperature range. They are physically compact and are well-suited for use in microprocessor-based products.

A variety of solid state sensors are available that measure temperature induced changes in resistance, frequency, current, or voltage. Optical sensors are available for measuring the temperature of a flame from a distance.

The devices mentioned above have certain applications to which they are well-suited. It is best to consult with the vendors of each of these devices to determine the particular applicability of a specific sensor. The key to making an appropriate selection is to understand what process conditions may contribute to an accidental release and what sensor would be best suited to measure those conditions. Some processes must operate in a very narrow temperature range and therefore require a sensor with high sensitivity and accuracy over a narrow range. A process may require a narrow operating range for producing the desired product but will be hazardous only if it operates well above or below that range. In such a case it may be appropriate to install two sensors; one with a narrow range for controlling normal operations and one with a wide range for monitoring upset conditions. For some processes a loss of temperature control will develop slowly. In such situations response time may not be as important as accuracy. For other processes a loss of temperature control will develop rapidly, and in these situations a rapid response time may be more important than accuracy.

Temperature Trip and Emergency Cooling Systems--

A temperature trip system is essentially the same as a pressure trip system. This type of control system monitors temperature and is activated when temperature has exceeded a specified limit or a specified rate of increase. When activated, the system responds in an attempt to shut the process down by eliminating the source of heat and often by providing a source of cooling. Usually the goal is to prevent an overpressure. Any decision about whether temperature or pressure measurement should be used as the basis for the trip system should be based on which would provide the most immediate and accurate indication of an impending system failure. Once activated, a trip system will usually disrupt the process, forcing at least a partial, temporary shutdown. The system should be designed to trip only when necessary. An intimate understanding of the chemistry and thermodynamics of the process is essential for proper design of this type of system.

A trip system may be designed to shut off the supply of heat or it may be designed to supply an emergency supply of cooling. Emergency cooling may be accomplished by a number of methods. External cooling may be supplied by flooding a heat exchanger or vessel jacket with cooling water. Internal cooling may be supplied by adding chilled solvent to the reaction melt. The solvent would not only cool the reaction but the extra dilution could slow the reaction rate. A somewhat drastic measure would be to intentionally poison the reaction by adding a material that is known to effectively stop its progress. The more drastic measure of automatically dumping the contents of a reactor into a diked, open area or into a supplementary containment vessel has been applied in some cases; however, dumping into an open diked area may not be appropriate where toxic or flammable materials are involved.

If a temperature trip system is designed to replace a pressure relief device, then the reliability of the trip system must be ten times that of the pressure relief device for the same application. Calculation of this reliability should be based on the cálculated fractional dead time (the proportion of the time for which a system will be in the failed state). This method considers both the fault-rate for the individual components and the frequency of proof testing. If a temperature trip system is designed to supplement an emergency relief device, then the designed reliability must be based on the consequences of a loss of temperature control. In a situation where the overpressure may be so rapid as to constitute an explosion, or where a loss of temperature control is likely to lead to an accidental release, it is probably appropriate to design the system to have a reliability again equal to ten times that of the emergency relief device.

Jacketed Vessels and Heat Exchangers--

Temperature control is usually achieved via a heat transfer fluid circulating through a vessel jacket or a heat exchanger. Such equipment requires some special considerations if temperature control is to be maintained.

All vessel jackets and heat exchangers must have adequate pressure relief. Most heat exchangers and vessel jackets are designed with valves on the inlet and outlet lines. An overpressure could occur if a warm material is added to a vessel whose jacket is closed at the inlet and outlet. The warm material would heat the contents of the jacket and result in a buildup of pressure. A similar event could occur with a heat exchanger if either the shell or the tubes were valved off and warm material were circulated through the other side of the exchanger. All vessel jackets and heat exchangers must be inspected regularly to prevent a leak between the heat transfer fluid and the reaction mixture.

General design principles for jacketed systems are found in many sources. ASME has design codes for jacketed equipment and heat exchangers. As mentioned above, it is important that all jacketed vessels be supplied with adequate pressure relief. Additional general design information is discussed in Section 4 of this document.

Obtaining Chemical and Thermodynamic Data--

As mentioned above, the more chemical and thermodynamic data available, the safer the design of the temperature control system. Where hazardous materials are involved, a safe system must be based on as much data as possible.

Most plants cannot generate chemical reaction rate and thermodynamic data. This type of information and data on potential side reactions must usually be obtained from a research and development laboratory. However, a number of methods are available for estimating the chemical hazards of a system without extensive laboratory work.

Thermodynamic calculations or computer programs used to estimate thermodynamic data may be used to calculate the potential energy available in a given molecule or system. This information can be combined with correlations to evaluate potential hazards.

A number of empirical tests using reaction mixtures provide data that will assist in the design of a safe temperature control system (these tests also give information that can help in the design of all of the reaction related control systems). Differential scanning calorimetry, accelerating rate calorimetry, differential thermal analysis, heat flow calorimetry, and a test method developed by DIERS will all provide information useful in the design of a temperature control system.

2.5.3 Control Effectiveness

Measurement and Control--

Table 2-15 lists a variety of temperature-sensing and measurement devices and certain performance information. In addition to a temperature range, each device will have a variety of other performance limitations, including items such as acceptable sensitivity, reproducibility, materials of construction, and reliability. Care must be taken when selecting an appropriate temperature sensing device. Substituting an existing temperature measuring device with a device more suited for the particular application may increase the system's reliability and hence decrease the potential for an accidental release.

One author has summarized a number of considerations that apply to thermocouple application (40). Thermocouples come in at least two grades related to error specifications of the American National Standards Institute (ANSI) and the Instrument Society of America (ISA). Thermocouples may change calibration over time depending on the temperature and operating environment. Often overlooked is that the accuracy with which a thermocouple measures the temperature of a process fluid depends on its size, shape and location. For

TABLE 2-15. TEMPERATURE SENSOR SELECTION GUIDE FOR NON-SEVERE SERVICE UNDER 932°F

Sensor Type	Point Readings	Average Readings
Filled Element	Fair to good	Fair
Thermistor	Fair to excellent for some applications	Fair to excellent for some applications
Thermocouple	Fair to good	Fair for some applications
Resistance Bulb	Fair to excellent	Fair to excellent

Source: Adapted from Reference 19.

example, a thermocouple that is too small for an application or improperly located may measure a local rather than a bulk temperature. This is especially relevant in certain equipment where poor mixing or bypassing might occur. Leads that are too long can lead to inaccuracies, as can electrical interference. The main point is that temperature control effectiveness depends on accurate sensor information, which depends in turn on proper application and installation.

There may be no external indication that a temperature sensing device is giving an incorrect reading. Some devices, such as thermocouples, require periodic calibration. The readout from some temperature-sensing devices, such as thermistors, may drift as the device ages. Mechanical devices may stick at some incorrect temperature. In situations where an incorrect temperature reading would significantly contribute to the potential for an accidental release it may be advisable to use two different varieties of temperature sensing equipment.

Programming the software for a typical temperature control system is often based more on empirical data than on a theoretical understanding of the process. This is because of the complexity involved in a system where a heat transfer fluid (which itself must be heated) is used to heat the wall of a process vessel which then heats a reaction melt where a heat producing or absorbing reaction is occurring. An empirical approach is adequate for handling normal operating conditions but may be inadequate for handling the abnormal event. Where hazardous materials are involved, it is therefore important to obtain as much chemical and thermodynamic data as possible and to prepare for the unexpected with temperature or pressure trip systems and adequate pressure relief.

Temperature Trip and Emergency Cooling Systems--

A temperature trip and emergency cooling system may be necessary where a toxic material is involved and where there are fairly well-defined temperature boundaries beyond which the system will be out of control. If no such temperature boundaries exist, or if the boundaries are not well defined, it may be preferable to operate the system with a pressure-activated trip system.

Careful consideration must be given to the consequences of an emergency cooling system. By its nature, an emergency cooling system will tend to temporarily shut down a portion of the process. The possibility of liquid reaction melts freezing, vapors condensing, or upstream materials accumulating must be considered to be certain that the emergency cooling system does not introduce new hazards. In addition, the thermal stress could have a drastic temperature change as a result of emergency cooling on the construction materials must be considered. A design evaluation such as a HAZOP study will help determine the safety of an emergency cooling system.

Jacketed Vessels and Heat Exchangers--

Some of the potential limitations of jacketed equipment and heat exchangers have been discussed above. There are some additional considerations specific to vessel jackets. One additional hazard is the possibility that a loss of temperature control would result from a jacket relief valve that relieves and does not reseat properly. Enough heat transfer fluid could escape to prevent adequate temperature control of the vessel. Another concern is that there be adequate flow and mixing of the jacket fluid to avoid temperature stratification. The location of entry and exit nozzles on the jacket may influence this. In spite of these limitations, controlling temperature via jacketed vessels and heat exchangers is usually preferable because of the ability to provide controlled, uniform heating.

Obtaining Chemical and Thermodynamic Data--

The test methods mentioned previously for use in designing a temperature control system will provide information about what temperature ranges are inappropriate for the system of interest. They will also give an idea about the magnitude of the disturbance that may result if these temperatures are exceeded. Interpretation of the test results must be made by a person with experience in the area because the test results are qualitative as well as quantitative and no guarantee exists that what happens in the test will happen in the plant. Tests, however, are better than no information at all.

Reliability of Temperature Control Components--

The reliability of temperature control depends on the reliability of the individual components that comprise the temperature control system. The reliability of a full multicomponent control system also depends on the architecture of the specific system. Table 2-16 presents reliability data for some individual components. Another factor affecting the reliability of temperature control, which is not as significant in the control of other variables discussed, is the relatively long response time of physical systems and of temperature devices to temperature changes. For critical applications, high reliability requires that delays in detecting and acting on changes in temperature under emergency conditions have been properly accounted for.

TABLE 2-16. TYPICAL FAILURE RATES OF TEMPERATURE CONTROL COMPONENTS

Component	Failure Rate (Failures/Year)
Sensor With Thermowell	
Thermocouple (TC)	0.52
Resistance Temperature Detector (RTD)	0.41
Temperature Transducer	0.88
Temperature Controller	0.29-0.38
Control Valve	0.25-0.60
Control Loop	1.73
Cooling Water Capacity	System reliability depends on specific design and reliability of individual components.
Refrigerated Brine Capacity	System reliability depends on specific design and reliability of individual components.

Source: Adapted from References 2, 8, 19, and 37.

2.5.4 Summary of Control Technologies

Table 2-17 summarizes major hazards or hazard categories associated with temperature, and the corresponding control technology for both new and existing facilities. Based on the preceding discussions of this section, numerous individual control technologies or procedural changes can be inferred for each category.

2.5.5 Costs

The costs of components for temperature measurement and control process modifications are presented in Table 2-18. These component types and costs are based on a typical installation. The costs presented provide an order-of-magnitude basis for evaluating the economic impacts of process modifications involving temperture measurement and temperature measurement and control systems.

2.5.6 Case Examples (42)

The explosion of a batch chlorinator caused the deaths of eight employees and extensive damage. The reaction temperature, which was controlled automatically by manipulating the chlorine flow, fell sharply when the thermocouple failed. Personnel stopped the agitator and shut off the brine cooling while the instrument was repaired, but delay in stopping the chlorine flow led to a high temperature and decomposition reactions. The explosion blew the reactor cover through the roof, drove the reactor into the floor, and ruptured chlorine and ammonia lines. The released flammable gases burned and caused the eight casualties.

In another example of loss of temperature control, localized overheating caused the failure of a refinery reactor operating at 17,225 kPa (2500 psi), which released a large cloud of about 250,000 lb of $>C_{10}$ hydrocarbons and H_2 that ignited and caused widespread explosions and fires. Four people were

TABLE 2-17. MAJOR HAZARD AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	New Facility	Existing Facility
Temperature	• Runaway reaction	• Reactant feed control system	• Change reactant feed control system
		• Emergency trip to shut down reactant feeds	• Add emergency trip to shut down reactant feeds
		• Emergency cooling systems	• Add emergency cooling system
		• Emergency dump systems	• Add emergency dump system
			• Change process chemistry
	• Thermal expansion	• Design to avoid blocked-in liquid-full piping and equipment	• Change design to avoid blocked-in liquid-full piping and equipment.
		• Emergency trip to shut down heating systems	• Add emergency trip to shut down heating systems
		• Emergency cooling systems	• Add emergency cooling capacity
		• Insulation for protection from external sources of heat	• Insulate to protect from external sources of heat
	• Property changes	• Temperature control system design	• Change temperature control system design
		• Temperature control system design	• Change process chemistry

(Continued)

TABLE 2-17 (Continued)

Process Variable	Hazard	New Facility	Existing Facility
	• Equipment or material failure due to excess or deficient temperatures	• Temperature control system design • Equipment selection • Materials of construction • emergency heating system • Emergency cooling system	• Change temperature control system • Change process chemistry • Change equipment type • Change materials of construction • Add emergency heating system • Add emergency cooling system • Change process chemistry

TABLE 2-18. COSTS OF COMPONENTS ASSOCIATED WITH PROCESS MODIFICATIONS FOR TEMPERATURE MEASUREMENT AND CONTROL SYSTEMS

Basis: 4 inch diameter piping Temperature range 0-250 degree F.	Capital Cost Range ($) (1986 Dollars)	Annual Cost Range ($/yr) (1986 Dollars)	References
Sensor/with Thermowell			
Thermocouple	200 - 300	30 - 45	40
Resistance Temperature Detector (RTD)	-	-	
Thermistor	-	-	
Integrated Circuit (I.C) Sensor	-	-	
Transmitter and Indicator	990 - 1,680	150 - 250	40
Temperature switch	160 - 710	24 - 108	40
Controllers			
Simple, single loop, PID	800 - 1,600	69 - 138	26,27,28,33
Simple, interactive, PID	1,600 - 3,000	138 - 260	4,20,23,25
Programmable,PID	2,000 - 6,000	173 - 519	
Control Valve	3,000 - 6,000	450 - 900	
Control Loop			
Conventional	6,000 - 12,000	910 - 1,800	Composite
Via process control computer	3,000 - 15,000	260 - 1,298	
Additional Cooling Water Capacity (10 degree approach, 30 degree range)	30 - 75 per gpm of capacity	4.55 - 11.36 per gpm of capacity	20
Refrigerated Brine Capacity (20 degree F evaporator)	3,000 - 8,000 per ton of capacity	450 - 1,200 per ton of capacity	20

injured and property loss was great. Overpressures were highly directional.

2.6 QUANTITY CONTROL

The two primary objectives of quantity measurement and control are to achieve proper process material ratios and the proper level and/or weight of materials in process or storage vessels. Failure to perform either of these functions could result in the overfilling or overpressuring of process equipment, which could lead to an accidental release.

2.6.1 Quantity Measurement and Control Hazards

Hazards associated with a failure of the two functions stated above are discussed below.

Process Material Ratios--

Failure to maintain process material ratios can have both chemical and physical consequences. For most chemical reaction systems, there are two types of reactants: limiting reactants and non-limiting reactants. Often the controlled flowrate of the non-limiting feed stream will be ratioed to the flowrate of the limiting feedstream. In this situation, one feed stream controls the flowrates of all other feed streams, and a failure to measure or control the quantity of this stream may result in losing control of the quantities of all of the other process streams. Depending on the chemical reaction involved, such a loss in control could result in an overpressure caused by excess heat or material generation. For the non-limiting constituents, deviation from an acceptable quantity range may also lead to overheating or overpressure.

Level Control--

A failure to monitor and control the level in a process vessel or a storage tank may result in the overpressure of a closed vessel or in the overflow of a vented vessel.

Process problems include disturbances that lead to a change in the chemical or physical properties of a system, resulting in a loss of quantity measurement and control. Altering the physical properties of a process stream may affect quantity measurement. For flowing streams, a quantity measuring device will often be calibrated for a stream of a certain composition; a change in that composition will often alter the accuracy of a flow meter. For many types of quantity sensing and measuring equipment, the presence of solids or foams may alter the accuracy of the system.

Quantity deviations or loss of control may be caused by some other control malfunction. For example, a system failure such as a loss of temperature control results in an acceleration in the rate of reaction, then the excess reaction rate may exceed the ability of the quantity control system to respond in reducing a reactant feed and result in an overpressure. As with all sensing and control equipment, a number of equipment-related malfunctions may result in a loss of quantity control. Improper application, poor design, defective equipment, fatigue failure or corrosion may all result in a failure to measure and control process quantities. Quantity control is often a flow control problem; therefore, reliable quantity control depends on reliable flow control. A quantity control system may act as a backup to a flow control system to shut down flow when quantities are too high. Flow control considerations and their role in process hazards are discussed in Section 2.3 of this document.

Since a quantity determination and control system will only be as accurate as the standard to which the measuring device has been calibrated, improper calibration or maintenance can result in a failure in the control system. Some types of quantity determination systems, such as weighing devices, are sensitive to conditions exceeding their range, to physical abuse, ambient conditions, and other factors. Good operating practices and operating personnel who understand the limitations of the device are important to ensuring reliable service from the equipment.

2.6.2 Technology of Quantity Control

Quantity measurement and control devices can be divided into several categories according to their function:

- Flow meters, either mass or volume;
- Weighing devices such as load cells; and
- Level measuring devices.

Controlling quantity with weighing devices and level measuring devices is usually accomplished via a trip system and/or alarm. A trip system will often be used to stop the feed of material once a certain weight or level of material is reached. If a level indicator is used in process equipment such as a distillation column, then a trip system may be used to alter a heating rate when a high level in a reboiler is reached. An alarm may be used in conjunction with a trip, or by itself with the quantity detection devices. Operating personnel must then decide what response to the alarm is appropriate. This type of arrangement will work only where the hazard potential associated with an overfill is low or where no appropriate controlled response to an overfill can be determined.

Flow Meters--

Probably more varieties of flow measuring devices are available than any other type of process sensing instrumentation. One author has assembled a list of well over 50 different flow-meter types (43). Flow measurement and control are discussed as a separate topic in Section 2.3 of this document.

Weighing Systems--

Weighing devices are usually used in batch operations. Weighing, a method of measuring and regulating the amounts of materials charged to a reactor, is preferred in situations where the feed material is difficult to handle. Solids, slurries, and extremely viscous materials are examples of materials that may better be quantified by weighing than by measuring flow.

Both mechanical and electrical weighing devices are available. Mechanical weighing systems are more common than electrical and include platform scales, hopper scales, tank scales and tank truck scales. Mechanical scales can be extremely accurate and are generally simple to maintain and operate.

Electrical weighing devices are often referred to as load cells. These devices have the advantage of being small and easy to install. Load cells give quick response, are not subject to the same type of wear as a mechanical scale, and provide a signal for a readout at a remote location.

It is important to design a weighing system so that the damaging effect of various environmental factors will be minimized. Methods for isolating the weighing device from vibration by strengthening support foundations or by providing vibration absorption should be considered. The design must also ensure that the system is unaffected by connecting pipe stresses. In some instances it may be necessary to add temperature compensation. Weighing devices should be housed to ensure adequate drainage and protection from moisture or chemical contamination.

Regular inspection and maintenance of weighing devices is essential. Mechanical devices in particular must be readjusted and serviced frequently to ensure accurate results.

Depending on the consequences of inaccurate weighing, a backup to the weighing system may be desirable. A level measuring device may be a suitable backup for a weighing device.

Level Measurement--

Level measuring devices have a number of different uses. A level measuring device may be designed to sound an alarm or activate a switch only if the level passes above or below some fixed point, or it may be used to give a continuous level readout accurate enough to precisely track inventories. Devices may be designed to give a local indication of process vessel levels or to send a signal to a flow controller. Thus, level detection may be used either as a backup for other control systems or as a primary control device. Some devices must actually contact the liquid to sense level while some can measure level without contacting the liquid. Some detectors function mechanically and some function electronically.

Probably the most common variety of level measuring device is the flat glass gauge. This device is composed of a shielded external loop, portions of which are made of glass. The liquid level is then observed in the glass portions of the loop. Some of these devices can send a signal to another location. Their advantage is that they provide a visual means of measuring the level in a vessel. They are often used as a backup for a more sophisticated variety of level measuring device. Other mechanical level detection devices, such as floats and displacers, are also available.

A common variety of level measuring device is the differential pressure level detector, which measures level by detecting the pressure difference between two different points in a tank. Electronic devices such as capacitance, ultrasonic, optical, and radiation level detectors are also available.

Generally, level devices must be inserted into process vessels and involve additional piping or fittings. Since fittings are a potential weak point for a process vessel, they must be designed to withstand the same conditions that the vessel is designed to withstand. Some applicability criteria for selected level detector devices are shown in Table 2-19.

TABLE 2-19. LIQUID LEVEL DETECTOR SELECTION GUIDE

Level Detector Type	Local Indicator	Transmitter		Switch	
		Clean Fluid	Difficult Fluid	Clean Fluid	Foaming Fluid
Float	Fair	Poor-Fair	Poor	Good	N/A
Level Gauge	Fair-Good	N/A	N/A	N/A	N/A
Capacitance Probe	Poor-Fair	Fair	Poor-Fair	Good	Poor-Fair
Conductivity Probe	N/A	N/A	N/A	Fair	Poor
Diaphragm	Poor-Fair	Poor	Poor	Fair	N/A
Differential Pressure	Fair-Good	Good	Fair	Good	N/A
Displacement	Fair-Good	Excellent	Poor-Fair	Excellent	N/A
Radiation	Good	Good	Excellent	Good	N/A
Ultrasonic	Fair-Good	Fair	Good	Good	Poor-Fair
Tape	Good-Excellent	Good	Poor-Fair	Good	N/A

Source: Adapted from Reference 19.

2.6.3 Control Effectiveness

The effectiveness of various approaches to maintaining quantity control is evaluated in terms of performance, limitations, and reliability.

Flow Measurement and Control--

The effectiveness and secondary hazards associated with flow measurement and control are discussed in Section 2.3.

Weighing Systems--

When functioning properly, weighing devices are an effective means of monitoring the quantity of material added to a process vessel; however, all weighing devices are sensitive to a variety of environmental factors that may impair their performance.

Vibration and other related mechanical disturbances (such as impact damage when a load is dumped onto a weighing device) can seriously affect performance. Accuracy, stability, and repeatability can all be affected by mechanical disturbances.

Temperature will affect the accuracy of most weighing devices. Most mechanical scales have built-in temperature compensation; however, most mechanical devices will not weigh accurately if subjected to a rapid temperature change. Electrical devices are also sensitive to temperature changes. Sometimes temperature compensation will be built into an electrical device, and sometimes it will be necessary to add temperature compensation. If several load cells are used to weigh the contents of a reactor, any nonuniformity in the temperatures of the load cells is likely to result in a weighing error.

Additional environmental factors, such as moisture and chemical contamination, can damage a weighing device.

Level Measurement--

Level measurement is sometimes used directly to control the flowrates of streams into and out of a process vessel. In some situations this may be a simpler method for controlling flows than direct flowrate measurement and control. In most process situations, however, vessel feed streams are not controlled by level detection, since the failure of a level detector to control feed flowrates could easily result in an overfill, an overpressure and, potentially, in an accidental release. Level detection devices are well-suited to be a backup to flow control by activating high or low level trip systems or alarms. Where level detection is used as the primary control device for process flows (this is often the case for filling and emptying storage tanks and sometimes for charging to batch reactors), then two different types of level detection devices should be used in series.

The operation of some varieties of level detection equipment makes them fairly product specific. These types of devices should be avoided where stream compositions may vary. Many level detection devices cannot accurately measure the level of foamy solutions.

Installation requirements for level detection equipment will influence the suitability of a particular device for hazardous chemical service. Flat glass gauges that stick out from the vessel must be protected from being sheared off during a collision. Flat glass gauges are also often the first point of failure during the overpressure of a pressure vessel. Some devices require two points of entry into a vessel, one of which is low in the tank and below normal liquid levels. This increases the possibility of leaks. Some require that a probe be inserted below the liquid level. Care must be taken to ensure that the construction materials of such a probe are compatible with the process conditions. Additionally, care must be taken to ensure that the additional obstruction of a probe is acceptable. Some probes can operate from the top of a vessel without contacting the liquid. These may be preferred in many instances; however, constructions materials are still important in devices that operate above the liquid level. The vapor phase in a process vessel is often more corrosive than the liquid phase.

Reliability of Quantity Control Components--

The reliability of quantity control depends on the reliability of the individual components that comprise the quantity control system. The reliability of a full multicomponent control system also depends on the architecture of the specific system. Table 2-20 presents reliability data for some individual components expressed as typical failure rates.

2.6.4 Summary of Control Technologies

Table 2-21 summarizes major hazards or hazard categories associated with quantity control, and the corresponding control technology or procedural categories for both new and existing facilities. Numerous individual control technologies or procedural changes can be inferred for each category.

2.6.5 Costs

The costs of components found in quantity measurement and control systems are presented in Table 2-22. These component types and costs are based on a typical installation. Since there are other types of systems, and many variations of systems within a given type, these costs only provide an order-of-magnitude basis for evaluating the economic effects of quantity measurement and control system process modifications.

2.6.6 Case Examples (42)

In one example of a loss of quantity control, overfilling of a salt dome storage well created a cloud of butane 1.25 mi. in diameter. Two explosions occurred, one 800-1000 ft. above grade. Twenty four people were injured.

TABLE 2-20. TYPICAL FAILURE RATES OF QUANTITY CONTROL COMPONENTS

Component	Failure Rate (Failures/year)
Load Cell Weigh System	3.75
Level Detection System	
Differential Pressure Transducer	1.71
Float System	1.64
Capacitance System	0.22
Electrical Conductivity Probes	2.36
Flow Totalizer	ca. 1.0

Source: Adapted from Reference 2, 8, 19, and 37.

TABLE 2-21. MAJOR QUANTITY RELATED HAZARDS AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	New Facility	Existing Facility
Quantity	• Incorrect reactant ratio, catalyst level, or inerts concentration • Incorrect level leading to overfilling or underfilling • Incorrect volume or mass of material leading to overfilling or underfilling	• Flow control design • Equipment selection • Level sensing and alarms • Weight sensing and alarms • Emergency trip system to shut down flow	• Change flow control system • Change type of equipment • Change or add level sensing and alarms • Change or add weight sensing and alarms • Change or add emergency trip system to shut down flow

TABLE 2-22. COSTS OF COMPONENTS RELATED TO PROCESS MODIFICATIONS FOR QUANTITY MEASUREMENT AND CONTROL SYSTEMS (EXCLUDING FLOW RATE MEASUREMENT. SEE SECTION 2.3)

Basis: Load cell weigh system: 10,000 gallon batch reactor.
Level system: 10,000 gallon vessel.
Flow totalizer: 33 gpm and 667 gpm.

Component	Capital Cost Range ($) (1986 dollars)	Annual Cost Range ($/yr) (1986 dollars)	References
Load cell weigh system	13,800	2,100	41
Level detection system -			
Sight gage	1,100	77	41
Float system	1,400	210	41
Capacitance system	2,400	365	41
Ultrasonic system	2,600	1,150	41
Nuclear system	14,900	2,260	41
Flow totalizer			
33 gpm	N/A	N/A	
667 gpm	N/A	N/A	

Another accident occurred in an ethylene producing plant in Holland, where failure of a level controller on a column caused cold liquid to pass out of the relief valve and into a carbon steel flare header, which cracked. The released cloud of 12,000 lb. of propylene ignited at a furnace 150 ft. away. Fourteen were killed, 104 injured and property damage was valued at almost 43 million dollars.

2.7 MIXING

Many processes can safely operate under a wide range of mixing rates. If there is an upper limit for a safe mixing rate, then it is likely to be set by foaming problems or some similar characteristic. Some processes must operate in a very specific mixing regime. Formulating processes often fall into this category. Usually there is a minimum mixing requirement below which reactants are not properly contacted or heat transfer is not sufficient and uniform.

There are three basic types of mixing systems:

- Direct mechanical mixing;
- Induced flow mixing; and
- Static mixing.

Direct mechanical mixing refers to mixing by blade agitators such as turbines or propellers. Induced flow mixing is accomplished with pumps or other devices, especially where a recirculating liquid stream back to a vessel is involved. Induced flow mixing can also involve ejectors and eductors. Static mixing involves using pipeline mixers that contain stationary mixing hardware elements inserted in the piping.

2.7.1 Mixing System Hazards

One group of authors has defined three basic categories of mixing problems (44).

- Loss of agitation;

- Insufficient mixing; and

- Excess energy input from mechanical friction.

A loss of agitation is usually the primary hazard in mixing systems. Hazards associated with a loss of mixing include:

- Incomplete reactions or formation of unwanted by-products;

- Reactant accumulation in poorly mixed zones; and

- Poor heat transfer with overall overheating or overcooling of a reaction or localized hot or cold spots.

The hazards of incomplete reactions or the formation of unwanted by-products is related to the chemical and physical properties of the unreacted materials or by-products. When there is insufficient mixing to contact reactants, a potentially dangerous excess of unreacted material can accumulate in the reaction vessel. With highly reactive materials, or in exothermic reactions, such a mixture could react at an uncontrolled rate if agitation began or if additional heat were added to the system. Even without this hazard, the unintended excess of a toxic reactant in downstream processing might cause problems. Failure to react a gaseous material because of insufficient agitation might lead directly to overpressure. Unwanted byproducts could include gaseous species leading to excess pressures, or corrosive materials that could damage equipment.

A loss of mixing control can cause poor heat transfer that results in localized hot and cold spots. Runaway reaction and/or overheating and overpressure could result. Decomposition reactions might also occur with heat sensitive materials. Hazards from overcooling include freezeups, solids deposition, and heat transfer surface fouling, with all their attendant process upsets, such as plugged lines, and accumulation of unreacted material. An accidental release could occur if adequate protection were not available to handle such an event. The hazards associated with a loss of temperature or pressure control are discussed in Subsections 2.3 and 2.4 of this manual.

A potential hazard associated with too much mixing is overheating as a resulting from the energy generated by mechanical friction. A well-insulated vessel left agitated for long periods of time may experience a temperature rise from mixing friction. Such a temperature rise could begin the chain of events that leads to an accidental release. For example, the additional heat input could start a decomposition reaction which could lead to gas evolution and overpressure.

A hazard associated with mixing is the generation of a static charge between the process stream and the process vessel. This is a particular problem where process vessels and piping are coated with glass or plastic materials that act as electrical insulators. Static charge can arc and result in fire and explosion if a flammable atmosphere is present.

Any event that leads to a dramatic change in the physical characteristics of the process materials being mixed may result in a decrease or loss of mixing. For example, a loss of heating resulting in frozen process materials would result in a loss of agitation. An increase in liquid viscosity could be caused by a decrease in temperature or by other unexpected conditions (e.g., improper reactant ratios). The viscosity of some liquids can increase with increased temperature, which is particularly hazardous if the increase in temperature leads to an increase in reaction rate and impaired mixing.

The hazard potential associated with freezing or viscosity changes is most severe where high speed, high shear mixing is involved.

Probably the most frequent cause of a loss of mixing control is some type of mechanical failure, which includes:

- Electric motor failure (either power outage or mechanical failure);
- Shaft seizure or breakage in the mixing equipment; and
- Breakage or detachment of a mixing impeller.

A variety of mechanical agitation devices are available. The possible failure modes of these devices depends on the specific type of equipment involved. Most systems involve rotating equipment subject to common failures such as bearing failure, shear pin failure, belt slippage or breakage, electrical malfunction, and others. Corrosion or wear may also cause a failure in the portion of the agitator system that actually contacts the process fluid. Agitators tend to experience more severe erosion and corrosion than do process vessels. Induced flow agitation systems may be subject to more potential failure modes than a mechanical agitation system. An induced flow system may fail because of a pump failure, valve failure, or piping failure.

Static mixers do not have rotating or moving components and are therefore not directly subject to all of the failure modes associated with mechanical agitators; however, a static mixer requires sufficient flow to induce adequate mixing. Therefore, a reduced flow through the static mixer may result in insufficient mixing. As with mechanical mixing systems, the static mixer is subject to corrosion or erosion from the process fluid.

Where mechanical agitation is involved in a batch process, it is possible for operators to forget to begin agitation at the proper time. Beginning agitation after materials have been charged may result in a runaway reaction, overpressure, and in an accidental release.

2.7.2 Technology of Mixing Control

Before an adequate mixing system can be designed it is important to determine what the effect of various mixing rates, including no mixing, may have on the process. One author has suggested that the effect of mixing on a chemical reaction system may be assessed using a heat flow calorimeter, which is capable of measuring instantaneous heat generation rates, heats of reaction, reactant heat accumulation, specific heats, and heat transfer data under simulated industrial process conditions (44).

Once the effect of mixing on a chemical process is understood, the effects of a mixing failure can be evaluated. It is then possible to design a system that minimizes the adverse effects of such a failure. If a mixing failure is potentially hazardous, it may be appropriate to provide an agitation detection system that is tied into flow and/or temperature control systems so that protective measures may be taken if agitation stops. An example would be to stop or reduce the flows of reactor feeds when agitation ceases. An agitation detection system does not necessarily have to directly measure agitation; it may be more appropriate to place a temperature probe or flow meter at a location that would be sensitive to changes occurring as a result of a loss of agitation. Where mechanical agitation is involved it is possible to monitor the mechanical equipment as an indicator of agitation.

As discussed above, in some situations it will be hazardous for an operator to begin a reaction addition sequence without agitation. For these situations it may be appropriate to provide an interlock that prevents the addition of a reactant when agitation is not present.

Proper maintenance of a mixing system is important. Mechanical agitators are used for batch or semibatch reactors of moderate size. They are appropriate when thorough and continuous mixing of the bulk liquid is required. An induced flow system may be used in conjunction with or independent of mechanical agitation. When applied by itself, an induced flow system is used when less agitation is required. A storage tank is often mixed using an induced flow mixing system. An induced flow system is also used when it is desirable to inject a reactant into a flowing stream before it is blended with the bulk solution. With this type of system there will be high shear and good mixing at the point of injection without going to the expense of more thorough agitation of the entire bulk solution. For all but small vessels, an induced flow system would be less expensive than a mechanical agitation system. An in-line static mixer is used in continuous processes where short duration mixing is satisfactory.

2.7.3 Control Effectiveness

People with experience in the area must determine the potential hazards associated with a loss of mixing control. The data obtained from a device such as a heat flow calorimeter may not be scaled up for a full-size process without interpretation or pilot plant experimentation.

When selecting an indirect method for agitation detection, it is important to evaluate whether the device selected will reliably detect a problem with agitation for all potential failure modes.

Mechanical agitation is generally very effective in providing good bulk mixing. Because mechanical agitation involves a large rotating piece of equipment, it is possible that a severe failure in the agitator will result in additional equipment damage. Agitators may become off balance, a situation that tends to become more severe as the device continues to rotate, and may destroy other portions of the system. If jammed, an agitator may shear and puncture a vessel. Most agitators have shear pins designed to prevent excessive torque on the agitator; however, with a shear pin an agitator system could stop at an inappropriate time because of excessive liquid viscosity and premature shear pin failure.

While providing a high rate of local mixing to the material in the pump-around loop, an induced-flow mixing system will usually provide less mixing to the bulk liquid than will a mechanical mixing system. This type of mixing system requires additional piping and therefore creates additional potential for a piping leak. It is possible to run the mixing loop pump with a valve closed or with a line plugged and be unaware that no mixing is occurring.

An in-line mixing device is generally physically smaller and less expensive than an agitator-type mixing system. Such a device is appropriate where single pass, short duration mixing is acceptable and where heat transfer performance is satisfactory and where gas or vapor evolution are not of concern. The extent of mixing for these devices depends on the length of the mixing section, the design of the internals and the flow rate through the section. Higher flow rates create a higher shear and better mixing, but they also require more energy input to overcome pressure drop.

Since mixing involves high shear, a mixing device is often more prone to corrosion and erosion than are other equipment components of a process system.

The reliability of mixing system depends on the reliability of individual components that comprise the system. The reliability of a full multicomponent control system also depends on the specific equipment and detailed design of the system. Table 2-23 shows reliability data, expressed as typical failure rates, for some individual components.

2.7.4 Summary of Control Technologies

Table 2-24 summarizes, from the point of view of both new and existing facilities, major hazards or hazard categories associated with mixing control, and the corresponding control technology. Numerous individual control technologies or procedural changes can be inferred for each category.

TABLE 2-23. TYPICAL FAILURE RATES OF MIXING SYSTEM COMPONENTS

Components	Failure Rate (Failures/year)
Mechanical Agitator (agitator motor only)	
- "Normal" Service	0.088
- "Severe" Service	8.8
Induced Flow Pump System (pump and motor only)	
- "Normal" Service	0.26
- "Severe" Service	8.8
Static Mixer	—[a]
Flow Switch	1.12
Pressure Switch	0.34
Tachometer	0.044

[a] Not Available

Source: Adapted from References 8, 19, 37.

TABLE 2-24. MAJOR MIXING-RELATED HAZARDS AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	Control Technology or Procedural Category	
		New Facility	Existing Facility
Mixing	● Loss of cooling ● Reactant accumulation ● Loss of heating	● Mixing detection ● Backup power supply ● Materials of construction ● Equipment selection	● Add mixing detection ● Add backup power supply ● Change materials of construction ● Change type of mixing system

2.7.5 Costs

Table 2-25 presents costs for components related to mixing system process modifications. These component types and costs are based on a typical installation. Since there are other types of systems and many variations of systems within a given type, these costs provide an order-of-magnitude basis for evaluating the economic effects of possible process modifications involving mixing systems.

2.7.6 Case Example (1)

In one instance of a loss of mixing control, the agitator stopped in a batch nitration reactor, but the process operator was unaware of this since instrumentation that would have stopped the acid feed to the reactor and given an alarm signal of agitator stoppage failed to work. When the agitator started up again, the reactor exploded.

2.8 COMPOSITION CONTROL

Varying a stream's composition affects its chemical and physical properties. Stream composition must usually fall within a fairly narrow range if a process system is to operate within design specifications. Proper design and operation of composition control systems may be important in preventing accidental releases.

2.8.1 Hazards Associated With the Loss of Composition Control

As a stream's composition varies from the design specifications, its chemical and physical properties also vary. The consequences are process-specific and may range from a lower quality product to an explosion and massive chemical release.

TABLE 2-25. COSTS OF COMPONENTS ASSOCIATED WITH PROCESS MODIFICATIONS FOR MIXING SYSTEMS

Basis: Mixing vessel volume: 10,000 gallon
Agitator power: 2 hp/1,000 gallons (20 hp)
Mixing rate: 10,000 gallons/15 minutes (667 gpm)
Static mixer diameter: 50 inches (200 gpm)
Induce flow pump: 667 gpm, 50 psig

Component	Capital Cost Range ($) (1986 Dollars)	Annual Cost Range ($/yr) (1986 Dollars)	References
Mechanical agitator (turbine), single impeller, impeller speed to 45 rpm) carbon steel	31,600	4,800	20
316 stainless steel	50,600	11,800	20
Induced flow pump system	8,300	1,250	20
Static mixer	N/A	N/A	N/A
Flow switch	530	80	22
Pressure switch	530	80	38

Physical properties such as vapor pressures and boiling and freezing temperatures will vary as composition varies. Some possible consequences include an overpressure caused by increased vapor pressure or a ruptured line caused by frozen process materials.

The chemical properties of a process stream will vary as the composition varies. Potential reactions and their corresponding rates will be affected by variations in the composition that could result in a variety of consequences. An altered composition could lead to a much more rapid reaction rate than desired, which could result in an overpressure, which could result in unwanted side reactions, or in an altered composition that could stop the desired reaction completely.

Primary composition considerations involve reaction rates. Chemical reaction rates are usually highly temperature dependent and are sometimes pressure dependent. For a system where chemical reactions are involved, anything that affects pressures or temperatures may affect stream compositions. Additionally, any alternate event (such as catalyst decay) that alters the nature of the chemical processes involved will affect stream composition.

Any number of mechanical or electrical malfunctions could alter stream compositions. A loss of flow control resulting from equipment malfunction may lead to a loss of composition control. No flow, too much flow or reverse flow of feed streams will all affect the composition of the process unit into which they feed. Contamination of the stream via the rupture of a heat exchanger tube is another example of a mechanical failure resulting in a loss of stream composition control.

The instruments used to monitor composition are often sensitive, and in some cases, prone to failure when exposed to adverse conditions. For some varieties there is a time lag from when the sample is taken until the results are known. In this situation it will be difficult to determine the actual composition at any given time if the composition is changing rapidly. The consequences of this time delay will depend on the nature of the reaction system involved.

A potential shortcoming of many composition monitors is that they often have a fairly specific range of materials that they can detect. An ideal detector would be able to monitor the products and reactant in a given reaction and all of the unwanted by-products and contaminants. Not selecting the best detector for the given application is another potential cause of loss of composition control.

Operational considerations also influence composition control. A lack of proper maintenance and training will contribute to a loss of composition determination and control. Composition determination systems require regular maintenance to function properly. Since most systems will monitor only a few components in the system, an operator must be trained to interpret what may actually be happening to the entire system.

2.8.2 Technology of Composition Control

A composition analyzer is an excellent device for monitoring the overall condition of the process, but it is rarely used directly to control a single variable such as flow because many process variables may affect composition, and rarely can composition be entirely controlled by one variable. An exception might be controlling pH by metering an alkaline or acid solution into a process stream. In most cases, a composition analyzer is usually used to warn operators when the composition of a process stream has deviated from normal conditions.

Composition analysis may be achieved by manually taking samples from a process stream and analyzing them in the laboratory or by installing an automatic on-line analyzer. An industrial equivalent exists for most common instruments used in laboratory analysis. Laboratory analysis of a process sample is usually much slower than on-line analysis, though it may be more accurate than on-line analysis. Where a process involves hazardous materials, some type of on-line composition analysis that provides an early warning of significant deviations may be desirable for critical streams.

Composition analysis equipment may be divided into two broad categories: devices that analyze for chemical species in stream, and devices that measure a chemical or physical property of the stream. Devices for measuring the chemical and physical properties of a stream are typically used where the cost of individual chemical species determination is excessive, or where the information obtained from a chemical or physical property measurement is adequate.

Common instruments used for on-line chemical species analysis include oxygen and moisture analyzers, chromatographs, ultraviolet analyzers, flame ionization analyzers, mass spectrometers, and infrared analyzers. Common chemical and physical properties measured on line include density, molecular weight, pH, viscosity, and oxidation-reduction potential. Some of these devices take a continuous reading from an in-line probe, some take continuous readings from a slip stream, while others automatically withdraw samples periodically.

The output from composition analyzers varies according to the type and sophistication of the instrument. Many of the physical and chemical property probes generate a signal that may be read directly from a scaled meter. These devices usually require periodic calibration. Most analyzers generate some type of graphical spectrum. The presence of various chemical species is then interpreted either by the operator or by the computer software available with some modern systems.

Two important considerations in the design of a composition analyzer systems are: 1) the location of the sensing device, and 2) the composition data required. These considerations might be addressed by a formal evaluation of the process using a hazard and operability study or some similar method that would help identify which stream compositions are most important from the perspective of safety and which stream compositions best indicate the status of the process.

Once the location and chemical species to be monitored have been selected, the analyzer is selected. It may be impossible or prohibitively expensive to monitor all the species desired. In such cases, the potential hazard associated with a change in composition and the amount of useful information that may be obtained from monitoring the composition must be weighed against the expense.

2.8.3 Control Effectiveness

Composition deviations indicate that something is potentially wrong with the process and provide information for diagnosing the problem's source. However, an incorrect result on a composition analyzer may cause a process problem to be missed and a good reading from a composition analyzer is no guarantee that everything is in order.

The information obtained from all varieties of composition instrumentation is limited. There are no perfect analyzers, and it is likely that no single analyzer is available to monitor every potential species within a given process stream. Since cost and complexity prevent every process stream from being monitored, it is important to carefully choose which streams should be monitored and which type of composition analyzer will give the most meaningful cost-effective information. As with all instrumentation systems accuracy, precision, sensitivity, and tolerance to overrange are important considerations in analyzer selection.

Interpreting the results from a composition analyzer is not necessarily straightforward. The problem with interpretation is two-fold: 1) the output from the device may be misread or misunderstood or 2) a correct instrument reading may be made and a wrong conclusion drawn. Instruments that provide a graphical trace are most easily misread or misunderstood. In chemical analyses impurities may be obscured by the signal of other species, the chemical character of a compound may make it invisible to the detector or it may respond more intensely than other compounds and appear to be present in a much higher concentration than it actually is. Any number of process deviations that may result in composition deviations, and correct interpretation of a composition analysis does not mean that a correct assessment of the state of the process will be made.

The maintenance requirements of a composition analyzer depend on the device. The sensing element in most devices must be cleaned and usually recalibrated regularly.

The reliability of composition control depends on the reliability of the individual components that comprise the composition control system. The reliability of a multicomponent system also depends on the architecture of the specific system. Table 2-26 presents reliability data expressed as typical failure rates for some individual components.

2.8.4 Summary of Control Technologies

Table 2-27 summarizes, from the point of view of both new and existing facilities, major hazards or hazard categories associated with composition and corresponding control technology. Numerous individual control technologies or procedural changes can be inferred for each category.

2.8.5 Costs

Costs of components related to composition measurement and control system process modifications are presented in Table 2-28. These component types and costs are based on typical installations. Since there are other types of systems, and many variations of systems within a given type, these costs

TABLE 2-26. TYPICAL FAILURE RATES OF COMPOSITION SYSTEM COMPONENTS

Component	Failure Rate (Failures/Year)
Composition Determination Equipment	
Density Sensor	
- indicator	—[a]
- transmitter	—[a]
pH Meter	5.88
Viscosity Sensor	
- indicator	—[a]
- transmitter	—[a]
Chemical Species Analyzers	
Chromatograph	30.6
Infrared Analyzer	1.40
Oxygen Analyzer	2.5-5.65
Moisture Analyzer (gases)	8.0
Conductivity Sensor	14.2-16.7

[a] Not available

Source: Adapted from References 1, 8, 19, and 37.

TABLE 2-27. MAJOR COMPOSITION-RELATED HAZARDS AND CONTROL TECHNOLOGY SUMMARIES

Process Variable	Hazard	Control Technology or Procedural Category	
		New Facility	Existing Facility
Composition	• Excess or deficient reactant • Excess or deficient catalyst • Excess corrodant • Excess toxic material in wrong stream	• Initial design and selection of composition analysis system	• Change type of composition analysis • Add composition analysis to process stream

TABLE 2-28. COSTS OF COMPONENTS ASSOCIATED WITH PROCESS MODIFICATIONS FOR COMPOSITION DETERMINATION AND CONTROL

	Capital Cost Range ($) (1986 Dollars)	Annual Cost Range ($/Yr) (1986 Dollars)	References
Composition Determination Equipment			
Density Sensor			
- indicator	500-1,500	92-275	20,41
- transmitter	1,500-5,000	275-917	20,41
Molecular Weight Sensor	5,000-10,000	917-8,834	20,41
pH Detector	4,000-5,000	734-917	20,41
Viscosity Sensor			
- indicator	2,000-5,000	367-917	20,41
- transmitter	5,000-12,000	917-2,200	20,41
Chemical Species Analyzers			
Chromatograph	10,000-40,000	1,834-7,340	20,41
Infrared Analyzer	3,000-10,000	550-1,834	20,41
Refractometer	4,000-10,000	734-1,834	20,41
Oxygen Analyzer	3,000-8,000	550-1,467	20,41
Moisture Analyzer	4,000-15,000	734-2,751	20,41
Spectrometer	10,000-40,000	1,834-7,340	20,41
Conductivity Sensor	700-2,000	129-367	20,41

provide an order-of-magnitude basis for evaluating the economic effects of possible process modifications involving composition measurement and control systems.

2.8.6 Case Example (42)

A day tank containing 6500 gallons of ethylene oxide became contaminated with ammonia. The tank ruptured, dispersing ethylene oxide into the atmosphere, where the cloud ignited and created an explosive force equal to 18 tons of TNT. One person was killed, nine were injured and property loss was valued at approximately 16 million dollars.

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SECTION 3

PHYSICAL PLANT DESIGN CONSIDERATIONS

The preceding section of this manual addressed process design considerations associated with basic process variables, the chemistry of a process, and process control. This section addresses the physical plant design and hardware of a process facility. Process and physical plant design taken together, whether of a new facility or of the modification of an existing facility, are the basis for preventing accidental chemical releases. In the words of one author: "The safety of the plant is determined primarily by the quality of the basic design rather than the addition of special safety features. It is difficult to overemphasize this point" (1). Safety features are part of that basic design, but in some facilities there may have been oversights in design and construction that warrant the addition of safety features to an existing facility.

Physical plant design considerations address the specific hazards caused by hardware failure, the proper design and construction of equipment to reduce those hazards, and the siting and layout of the equipment within the process facility. Specific hardware-related prevention measures can be identified to reduce the probability of accidental chemical releases.

General and detailed principles for the design of chemical process facilities comprise a vast technical literature. It is not within the scope of this manual to review all aspects of design, nor the intent of this manual to be used for design. The reader is referred to other technical literature for these purposes. It is the purpose here to highlight significant general considerations related to accidental release prevention.

Since the fundamental purpose of the physical plant and its equipment is to contain the chemicals under normal process operating conditions and within limited ranges of deviation, sound design practices that are thoroughly understood and faithfully followed are essential to prevent releases. Design principles related specifically to release prevention can be grouped into four broad categories:

- Standards, codes, recommended practices, and guidelines;
- Siting and layout;
- Miscellaneous considerations; and
- Equipment.

Each of these categories is discussed in the subsections that follow. Some important potential hazards and their control, related to the equipment and its layout in a process facility, are examined.

3.1 STANDARDS, CODES, AND RECOMMENDED PRACTICES

Equipment used in a process facility must be selected to function under the specified process conditions and under upset conditions; it must ensure containment of the chemicals being processed and must be resistant to fire and explosion. To help industry meet these requirements, numerous codes, standards of practice, recommended practices, and guidelines (referred to hereafter as standard design criteria) exist for categories and specific kinds of equipment. Different organizations developed standard design criteria over the years in response to knowledge gained from actual accidents or in anticipation of operating and safety problems based on technical analysis. Many of the standard design criteria were developed to meet the needs of property insurer's and worker health and safety concerns. It is beyond the scope of this manual to even present a detailed summary of all the standard design criteria applicable in the chemical process industries. Table 3-1, however, lists some major organizations involved in developing such standard design criteria. Table 3-2 summarizes some of the areas applicable to chemical process facilities (2).

Two major equipment categories addressed by codes are vessels and piping. Table 3-3 shows the design and physical components of vessels covered by the American Society of Mechanical Engineer's (ASME) code for pressure vessels (3). This is shown as an example of how much detail must be addressed by fabricators and constructors of process equipment and facilities. This code has been adopted as a legal standard in many areas. For piping, an important code was developed by the American Petroleum Institute (API); it applies to petroleum refineries and petrochemical plants, and may be applicable to other chemical process facilities as well (4). Many individual companies have their own standard design criteria, especially major corporations in the chemical process industries. Design criteria must always be carefully scrutinized when toxic chemicals are involved, especially in new situations, because the such criteria have often been developed for known sets of conditions, and it is possible that adherence to a standard criterion such as a code without a full appreciation of its basis or limitations could lead to unforeseen secondary hazards.

In the context of accidental release prevention, any standard design criteria, even codes, should be viewed as a minimum basis or starting point for equipment and plant design. Many specific situations may suggest more stringent specifications than the standard design criteria require. This if often an overlooked aspect of code and standards compliance that can lead to problems.

3.2 SITING AND LAYOUT CONSIDERATIONS

Siting and layout considerations are an important aspect of accidental release prevention. Siting refers to the location of the process facility within a community, while layout refers to the positioning of equipment within the process facility.

TABLE 3-1. SOME OF THE MAJOR ORGANIZATIONS PROVIDING CODES, STANDARDS, RECOMMENDED PRACTICES, AND GUIDELINES FOR EQUIPMENT FOR CHEMICAL AND ALLIED INDUSTRY PROCESS PLANTS

Name	Abbreviation Symbol
Technical and Trade Groups	
American Water Works Association	AWWA
Air Conditioning & Refrigeration Institute	ARI
Air Moving and Conditioning Association	AMCA
American Association of Railroads	AAR
American Gas Association	AGA
American Petroleum Institute	API
Chlorine Institute	CI
Compressed Gas Association	CGA
Cooling Tower Institute	CTI
Chemical Manufacture's Association	CMA
Manufacturers Standardization Society	MSS
National Electrical Manufacturers Association	NEMA
Pipe Fabrication Institute	PFI
Scientific Apparatus Makers Association	SAMA
Society of Plastics Industry	SPI
Steel Structures Painting Council	SSPC
Tubular Exchanger Manufacturers Association	TEMA
U.S. Government Agencies	
Bureau of Mines	BM
Department of Transportation	DOT
U.S. Coast Guard	SCG
Hazardous Materials Regulation Board	HMRB
Federal Aviation Administration	FAA
Environmental Protection Agency	EPA
National Bureau of Standards	NBS
Occupational Safety and Health Administration	OSHA
Testing Standards and Safety Groups	
American National Standards Institute	ANSI
American Society for Testing and Materials	ASTM
National Fire Protection Association	NFPA
Underwriters Laboratories, Inc.	UL
National Safety Council	NSC
Insuring Associations	
American Insurance Association	AIA
Factory Insurance Association	FIA
Factory Mutual System	FM
Oil Insurance Association	OIA

(Continued)

TABLE 3-1 (Continued)

Name	Abbreviation Symbol
Professional Societies	
American Conference of Governmental Industrial Hygienists	ACGIH
American Industrial Hygiene Association	AIHA
American Institute of Chemical Engineers	AIChE
American Society of Mechanical Engineers	ASME
Amer. Soc. of Htg., Refrig. & Air-Cond. Engs.	ASHRAE
Illumination Engineers Society	IES
Institute of Electrical and Electronic Engineers	IEEE
Instrument Society of America	ISA

Source: Adapted from Reference 2.

TABLE 3-2. SOME OF THE AREAS COVERED BY CODES, STANDARDS, GUIDELINES, AND RECOMMENDED PRACTICES OF DESIGNATED ORGANIZATIONS (SEE TABLE 3-1 FOR SYMBOLS DEFINITIONS)

Accident Case History - NFPA, NSC, AIA, FIA, FM, OIA, AIChE, AGA, API, CMA, USCG, OSHA

Plant & Equipment Layout - NFPA, NSC, AIA, FIA, FM, OIA, AWWA, AAR, API, CGA, CMA, USCG, HMRB

Electrical Area Classification - ANSI, NFPA, NSC, AIA, FIA, FM, OIA, API, CMA, USCG, OSHA

Electrical Control and Enclosures - ANSI, NFPA, UL, NSC, AIA, FIA, FM, OIA, IEEE, ISA, ARI, MCA, NEMA, USCG, OSHA

Grounding and Static Electrical - ANSI, NFPA, UL, NSC, AIA, FIA, FM, OIA, IEEE, API, NEMA, USCG, OSHA

Power Wiring - ANSI, NFPA, UL, FIA, FM, OIA, IEEE, API, NEMA, USCG, OSHA

Lighting - ANSI, NFPA, UL, NSC, FM, IEEE, IES, NEMA, USCG

Emergency Electrical Systems - NFPA, AIA, FM, IEEE, AGA, NEMA, USCG

Instrumentation - ANSI, ASTM, NFPA, UL, AIA, FIA, FM, OIA, IEEE, ISA, AWWA, ARI, API, CGA, SAMA, USCG, HMRB, NBS

Shutdown Systems - NFPA, UL, AIA, FIA, OIA, API, USCG

Pressure Relief Equipment Systems - NFPA, AIA, FIA, FM, OIA, ASME, API, CI, CGA, USCG, HMRB, OSHA

Venting Requirements - NFPA, FIA, FM, API, USCG, HMRB

Product Storage and Handling - ANSI, NFPA, AIA, FIA, FM, OIA, AIChE, AAR, API, CI, CGA, MCA, USCG, OSHA

Piping Materials and Systems - ANSI, ASTM, NFPA, UL, NSC, AIA, FIA, FM, NBS ASHRAE, IES, AWWA, ARI, AGA, API, CI, CGA, MSS, NFPA, PFI, SPI, USCG, HMRB,

Materials of Construction - ASTM, ANSI, NFPA, UL, NSC, AIA, FM, OIA, ISA, AWWA, CI, CGA, CTI, MCA, TEMA, USCG, HMRB, NBS

Insulation and Fireproofing - ANSI, ASTM, UL, AIA, FM, OIA, ASHRAE, USCG

Painting and Coating - ANSI, ASTM, UL, AIChE, AWWA, SSPC, HMRB, NBS, OSHA

Ventilation - ANSI, NFPA, UL, NSC, FIA, FM, ACGIH, AIHA, BM, USCG

(continued)

TABLE 3-2 (continued)

Dust Hazards - ANSI, NFPA, UL, NSC, FIA, FM, ACGIH, AIHA, BM, USCG

Noise and Vibration - ANSI, ASTM, NFPA, UL, NSC, AIHA, AIChE, ASHRAE, ISA, ARI, AMCA, AGA, API, NFPA, EPA, OSHA

Lubrication - ANSI, NFPA, ASME, AMCA

Fire Protection Equipment - ANSI, NFPA, UL, NSC, AIA, FIA, OIA, AWWA, API, CGA, CMA, NEMA, BM, USCG, OSHA

Safety Equipment - ANSI, UL, NSC, FM, ACGIH, AIHA, CI, CGA, MCA, BM, USCG, OSHA

Pumps - ANSI, UL, OIA, AIChE, AWWA, HI NFPA, USCG

Fire Pumps - ANSI, NFPA, UL, FM, IEEE, HI, USCG

Fans and Blowers - FM, ACGIH, AIHA, ASME, ARI, AMCA, USCG

Compressors - AIA, FM, OIA, ASME, ASHRAE, ARI, USCG

Air Compressors - ANSI, AIA, FM, USCG

Steam Turbines - AIA, FM, OIA, IEEE, USCG

Gas Turbines - NFPA, FIA, FM, OIA, AGA, USCG

Gas Engines - NFPA, FM, OIA, USCG

Electric Motors - ANSI, NFPA, UL, IEEE, CMA, USCG

Shell & Tube Exchangers - AIChE, ASME, ASHRAE, ARI, AGA, CGA, PFI, USCG

Air-Fin Coolers - OIA, ASHRAE, ARI, USCG

Cooling Towers - NFPA, FM, OIA, CTI

Boilers - ANSI, NFPA, UL, NSC

Fired Heaters - ANSI, NFPA, UL, FIA, FM, OIA, ASME, USCG

Combustion Equipment & Controls - ANSI, NFPA, UL, NSC, FIA, FM, OIA, USCG

Refrigeration Equipment - ANSI, NFPA, UL, FM, ASHRAE, ARI, USCG

(continued)

TABLE 3-2 (continued)

Dust Collection Equipment - NFPA, FIA, FM, USCG

Pneumatic Conveying - ANSI, NFPA, FIA, USCG

Solids Conveyors - CMA

Storage Tanks - NFPA, UL, OIA, AWWA, CI, USCG, NBS, OSHA

Pressure Vessels - NFPA, NSC, AIA, ASME, ARI, CGA, HEI, DOT, USCG, OSHA

Material Handling - NFPA, NSC, CMA, OSHA

Jets and Ejectors - HEI, USCG

Gear Drives Power Transmission - ANSI, NSC, AIA, AGMA, USCG

Stacks and Flares - OIA, USCG, FAA

Drain and Waste Systems - AIChE, AWWA, CMA, USCG

Inspection and Testing - ASTM, NFPA, NSC, AIChE, ASHRAE, IEEE, AMCA, ABMA, API, AGMA, AWWA, CGA, CTI, HEI, HI, MSS, NFPA, PFI, DOT, USCG

Source: Adapted from Reference 2.

TABLE 3-3. PHYSICAL COMPONENTS, DESIGN, AND FABRICATION FEATURES OF VESSELS COVERED BY ASME CODES AS INDICATED

Component	ASME Code Section
Component Codes	
Full face gasket	UA-6, UA-45
Welded connection	UW-15, UW-16, Fig. UW-16.1
Reinforcement pad	G-37, UG-40, UG-41, UG-82, UW-15, UA-280
Code termination of vessel	U-1 (e)
Lap Joint stub end	UG-11, G-44, UG-45
Loose type flange	UG-44, UA-45 to 52, Fig. UA-48
Ellipoidal head, pressures, int.	UG-32, Ext.UG-33, UA-4, UA-275
Head skirt	UG-32, Fig. UW-13.1, UW-13
Optional type flanges	UG-14, UG-44, UW-13, Fig. UW-13.2, UA-45 to 52, UA-55, Fig. UA-48, Appendix S
Nuts and washers	UG-13, UCS-11, UNF-13
Studs and bolts	UG-12, CS-10, UNF-12
Applied linings	Part UCL., UG-26, Appendix F
Integrally clad plate	Part UCL, Appendix F
Corrosion	G-25, CS-25, UCL-25, UA-155 to UA-160
Stiffener plate	UG-6, UG-22, UG-54, UG-82
Support lugs	G-6, UG-54, UG-82, Appendix G
Longitudinal joints	UW-33, UW-3, UW-35, UW-9
Tell tale holes	UG-25, UCL-25
Attachment of jacket	Fig. UA-104, Fig. UA-105
Jacket vessels	UG-28, UG-47(c) Appendix IX
Plug welds	UW-17, UW-37
Bars and structural shapes	UG-14, UW-19, Fig. W-19.2 Stayed surfaces, UG-47
Stay bolts	UG-14, UG-27f, UG-47 toUG-50, UW-19, Fig. UW-19.1
1/2 Apex angle	G-32
Support skirt	UG-6, UG-22, UG-54, UA-185 to UA-189, Toriconical head pressures, Int. UG-32, UG-36, Fig. UG-36, Ext. UG-33, A-275
Studded connections	UG-43, UG-44,W-16, Fig. UW-16.1, UW-15
Optional type flange	UG-14, UG-44, UW-13, Fig. W-13.2, UA-45 to 52, UA-55, Fig. UA-48, Appendix S
Bolted flange, spherical cover	UA-6
Manhole cover plate	UG-11, UG-46
Flued openings	UG-32, UG-38, Fig. UG-38

(Continued)

TABLE 3-3 (Continued)

Component	ASME Code Section
Component Codes	
Yoke	UG-11
Studs, nuts, washers	UG-12, UG-13, UCS-10, UCS-11, UNF-12, UNF-13
Spherically dished covers	UA-6, Fig. UA-6
Flat face flange, Appendix Y	Fig. UA-1110
Welded connection	UW-15, UW-16, Fig. UW-16.1
Opening	UG-36 to UG-42, UA-7, UA-280
Multiple openings	UG-42
Non-pressure parts	G-6, UG-22, UG-55, UG-82
Hemispherical head, pressures, int.	UG-32, UA-4, UA-3, Ext. UG-32, UA-275
Unequal thickness	W-9, Fig. UW-9, UW-13, Fig. UW-13.1
Shell thickness	UG-16, UHA-20, Pressures, Int. UG-27, UA-1, UA-2, UA-274, Ext. UG-28, UA-270 to UA-272
Stiffening rings	UG-29, UG-30, UA-272
Welded connection	W-15, UW-16, Fig. UW-16.1
Flat head	UG-34, Fig. UG-34, UW-13, UG-93(d)(3), Fig's. UW-13.2 & UW-13.3
Openings, flat heads	UG-39
Backing strip	Table UW-12, UW-35
Circumferential joints	UW-3, UW-33,UW-35
Flat head	UG-34, Fig. UG-34, UG-39
Tube sheet, no code, TEMA acceptable,	U2(g)
Tubes	UG-9, Pressure, Int. UG-31, Ext. UG-28, UG-31
Baffle	G-6
Channel section, cast steel	UG-24 part UCS, UHA, Cast Iron, UC1
Integral type flange	UG-44, UA-45 to UA-52, Fig. UA-48, UA-55, Appendix S
Reinforcement pad	UG-22, UG-37, UG-40, UG-41, UG-82, UW-16, UA-280
Compression ring	UA-5
1/2 Apex angle	UG-32
Conical heads, pressures	Pressures, Ext. UG-33, UA-275, Int. UG-32, UG-36, Fig. UG-36, A-4,
Small welded fittings	UG-11,UG-43, UW-15, UW-16, Fig. UW-16.1, Fig. UW-16.2

(Continued)

TABLE 3-3 (Continued)

Acitivity	ASME Code Section
Component Codes	
Threaded openings	UG-43(e)
Heat attachment	UW-13, Fig. UW-13.1
Fillet welds	UW-18, UW-36 Table UW-12
Knuckle radius	UG-32, UCS-79
Torispherical head, pressures	Int. UG-32, UA-4, Ext. UG-33, A-275
General Design and Fabrication Codes	
Heat Treatment	UG-85, UW-10, UW-40, UCS-56, Table UCS-56, UCS-79(d), UCS-85, UNF-56, UHA-32, UHA-105, & UCL-34
Inspection	UG-90 thru UG-97, U-1 (j)
Joint Efficiency	UW-12, & Table UW-12
Lethal Service	UW-2(a), UCD-2, & UC1-2
Loadings	UG-22
Low Temperature	UG-84, UW-2(b), UCS-65, UCS-66, UCS-67, UNF-65, & UCL-27
Materials	UG-5 thru UG-15, UG-18, UG-77, UCL-11 & UW-5, Tables NF-1 & NF-2
Pressure, Design	UG-19, & UG-21, Max. Allowable Working UG-98
Temperature, Design	UG-19, UG-20
Pressure Vessels Subject to Direct Firing	UW-2(d), U-1(h)
Radiographic Exam	UW-11, UW-51, UW-52, UCS-57, UNF-57, UHA-33, & UCLK-35, Spot Exam of Welded Joint UW-52, No Radiograph "W-11(c)
Relief Devices	UG-125 through UG-136, App. XI
Repairs	UG-78, UW-38, UW-40(d)
Stress	Max, Allow., Value UG-23, W-12(c), UNF-23, UHA-23, UCL-23
Test, Hydrostatic	G-99, UC1-99, UCL-52, & UA-60, Pneumatic UW-50 & UG-100; Proof, UG-101; Non-Destructive, UG-103, UNF-58, & UHA-34; Mag. Part, UA-70 thru UA-73; Liq. Pene, UA-91 thru UA-95; Ultrasonic, UA-901 thru UA-904; Impact, UG-84, UCS-66, UHA-51,NF-6
Stamping and Data	UG-115 thru UG-120
Unfired Steam Boilers	UW-2(c), U-1(g)

Source: Adapted from Reference 3.

3.2.1 Siting

Siting, as related to accidental chemical releases, is usually thought of in terms of mitigating the consequences of a release rather than in preventing it. Siting from the perspective of mitigation, the consequences of a release is dealt with in a companion manual on mitigation in this series. Certain conditions of siting, however, can influence the probability of a release. These conditions primarily are related to natural disasters and climate, but also to circumstances at neighboring facilities, or transportation accidents, that could play a role in causing releases.

Examples of natural phenomena and disasters include lightening, windstorms, floods, earthquakes, subsidence, and landslides. Climatic factors include rainfall patterns, temperature extremes, and temperature variability.

These factors directly influence physical plant design, and if not properly accounted for they can result in hazardous design deficiencies. For example, a facility in a flood-prone area may require different types of foundations for storage tanks or process equipment. Ambient temperatures might be important if a line freezeup in a particular process could lead to a failure that causes an accidental release.

Lees discusses siting from a process hazard perspective and cites a number of literature references on siting (1).

Materials of construction are influenced by the temperature extremes the facility is subjected to and by any corrosive characteristics of the ambient air. For example, areas of high humidity, or the presence of nearby salt water or of a facility that emits a corrosive gas should influence the selection of construction materials. The level of dust in the air and the potential for severe dust storms may require special protection for certain types of equipment. Special precautions should be taken wherever subfreezing temperatures are common. Such precautions may include the addition of extra insulation or heat tracing and may dictate the types of seals and gaskets used on equipment.

Material strength requirements are influenced by the frequency of severe wind and weather conditions. Process equipment and their supporting structures may need extra reinforcement or protection where high winds or severe hail occur.

As a final example, the presence of a neighboring facility where a fire, explosion, or accidental release could trigger an incident in one's own plant may require consideration.

3.2.2 Layout

Layout refers to the placement and spacing of the various parts of a process facility, including the individual equipment in the various parts. A properly designed layout reduces the potential for and the consequences of an accidental release by enhancing process operability and by segregating hazardous areas within the facility. A great deal has been written on plant layout in the technical literature. Both the Chemical Manufacturers Association (CMA) and the National Fire Protection Association (NFPA) have issued standards or guidelines for plant layout (5).

Increased distances between process units tend to reduce the potential for, and the impact of an accidental release. The value of distance depends on the nature of the hazard. An explosion in one process unit can result in an accidental release in another process unit because of damage from the blast wave. The blast wave pressure front travels rapidly but its intensity decreases rapidly with distance. A vapor cloud associated with an accidental release travels much more slowly than a blast wave but usually affects a larger area before it is diluted enough to present no danger. A fundamental layout consideration where flammable or explosive vapor clouds may occur is to locate away from obvious ignition sources. While unexpected ignition sources may still ignite a flammable cloud, there is no reason to make the process easier.

Whenever possible, a quantitative method should be used to aid in choosing the spacing between process units. This can be done by first developing a relative hazard ranking of individual process units. One method of quantifying the hazard of a given process unit assigns a hazard number to various features of a substance or process. These numbers are based on an arbitrary scale. The numbers for various portions of the system are combined by multiplying by weighting factors and summing the results to create an overall hazard rating. The Dow Index is an example of this type of approach for ranking processes in terms of fire and explosion potential (6). An extension of the DOW Index is the Mond Index, which extends the ranking to include toxicity. Other methods for quantifying relative hazards and developing spacing requirements have been developed (7,8,9).

A list of basic concepts for achieving optimal layout has been assembled by Lewis (8):

- Roads need to allow entry to the plant from at least two points on the site perimeter, preferably from opposite sides.

- All units in the area with a moderate or high fire risk should have access for emergency vehicles from at least two directions.

- Control rooms, amenity buildings, workshops, laboratories and offices should be sited close to the site perimeter.

- Pipebridges should be laid out to minimize easy transfer of incidents from one unit to another. Key pipebridges should be assessed independently of adjacent units for hazard potential.

- Wherever possible, units of high risk should be separated from each other by units of mild, low or medium risk.

- Appropriate distances should separate units from identified ignition sources, such as furnaces, electrical switchgear, flarestacks, etc.

- Control rooms, amenity buildings, workshops, laboratories and offices should be adjacent to units of mild or low risk, which act as a barrier from higher risk units. Medium risk units are only acceptable adjacent to populated buildings (a) if lower risk units are not available for separation purposes, and (b) if the risk level is only just inside the "medium" band of Overall Risk Rating as assigned by the Mond Index method.

- Units with the highest values of the Major Toxicity Incident Index, assigned by the Mond Index method, should be suitably distant from all facility buildings containing many people, and also from activities outside the works boundary. (This particularly applies to the locations of schools, hospitals, places of entertainment etc.)

- Units having the highest values of the Aerial Explosion Index, assigned by the Mond Index method, should not be located close to a plant or facilities boundary; they should be separated by areas occupied by low risk activities with low population densities (up to 25 people per acre).

- Major pipebridges with a medium to high "Overall Risk Rating" (assigned by the Mond Index method) should be located so that they are at minimal risk from incidents on tall process units and from transport accidents arising from the regular movement of vehicles taking materials to or away from the plant site.

- Units previously and separately assessed for hazard ratings can be combined into a larger single unit providing (a) the risks are similar, (b) the potential direct and consequential losses do not become excessive and (c) a reassessment of the rating of the combined unit is acceptable.

- As far as possible, units should be laid out for a logical process flow to minimize the pipebridge requirement.

- Pipebridge routes should be chosen so that they are not likely to contribute to the spread of an accident. Alternative route selection should allow as much process control as possible.

- Storage units should be adequately separated from operational areas and, as far as possible, located away from road and rail traffic routes within the plant site.

In general, optimum spacing arrangements provide straight, unobstructed access ways that are continuous from one end of a processing unit to the other and are connected to roads that surround the unit. Piping should be laid out in a way that minimizes the amount of piping. Piping associated with various utilities and process units should be segregated, since this will help to avoid confusion during operations. Adequate spacing must be provided for maintenance and construction. More than one escape route should be available for any location within the facility. In the initial facility design, extra room should be provided for future expansion to avoid creating future congestion hazards.

The layout for indoor process units requires special considerations. Hazardous or flammable vapors can accumulate in an indoor facility. Proper ventilation is a primary consideration for indoor facilities that handle hazardous materials. Many air changes per hour with little recirculation may be in order where a hazardous material is involved. Any potential leak source should be protected. Vents and pressure relief discharge lines which may release toxic or flammable materials should be piped to a safe area. The holdup of hazardous materials inside of process buildings should be minimized and generally limited to material in process equipment and piping. Some additional considerations for indoor facilities are listed in this manual in Section 3.3.4.

A safe control room is essential if a plant is to respond to an accidental release once it has occurred. As far as possible, a control room should be located in an area where exposure to fires, explosions or toxic releases is minimum. Wherever a control room is located, it should be designed to minimize the potential for injury to the employees in the event of an accident. Examples of precautions include, explosion shielding, shatterproof windows, a ventilation system that provides clean air while keeping the control room under slight positive pressure, and extra fire protection. If a control room is located within a process unit, then other buildings such as laboratories, lunchrooms or offices should not be added onto the control room. Support structures where personnel tend to congregate should be located outside of the processing area.

Many of the layout precautions listed above are necessary for the sake of fire prevention. Additional layout considerations specifically for fire protection are discussed in Subsection 3.3.4.

3.2.3 Storage Layout Considerations

The arrangement of storage facilities follows the same general principles just discussed for general siting and layout. Storage facilities may merit special consideration, however, because they contain large inventories of chemicals.

Storage near high-hazard process areas and loading and unloading terminals should be the minimum required for the needs of the process or shipping requirements. Storage facilities should be located on, at most, two sides of a processing area so that the area is open on at least two sides. Inventory should be kept to a minimum. Tank storage areas should be located away from offices and other locations where people congregate. A tank storage area should be located as far from a community population center as possible. Prevailing wind direction should be considered so that the effects of a large release from storage facilities are minimized. The natural ground contour should be considered so that runoff from a spill would not contaminate a large area or would not find its way to a source of ignition.

One basis for selecting tank spacings are NFPA standards (5). These are based on flammable materials but are a useful guide for separating flammable and toxic materials. Two materials that may react and generate heat upon contact should not be stored within the same diked area. A chemical should not be stored in a diked area with a tank constructed of material that it would react with. For example, concentrated hydrochloric acid should not be stored in a diked area with a carbon steel tank that contains another hazardous chemical.

Adequate spacing for fire control and maintenance should be available for all tanks. Access roads should surround groups of tanks. As far as possible, tanks should be located away from heavily traveled roadways to minimize the potential for vehicle collisions with tanks. Fittings and pipe runs should be protected from vehicle collision. This applies especially to pipe bridges with pipes carrying toxic chemicals. Appropriate fire protection in the form of deluge systems, and/or foam systems should be permanently in place.

3.2.4 Miscellaneous Design Considerations

A number of miscellaneous design considerations are an inherent part of physical plant design. These include:

- Availability and dependability of utilities;
- Operability;
- Fail-Safe Design;
- Fire prevention and protection;
- Electrical system requirements;
- In-process inventories; and
- Special safety requirements.

Availability and Dependability of Utilities--

The loss of a utility can result in an accidental release if control of the process is consequently lost. The potential for an accidental release may be reduced if two principles are followed in designing a utility system.

The first principle of safe utility design is, if the failure of a utility to a portion of a facility can result in a loss of control in that section of the facility, then that utility should be supplied with a backup in at least that portion of the facility. A facility electrical system backup could be a diesel generator system. An instrument air system could be backed up with a nitrogen system. Backup for a utility does not mean that there must be a duplicate of the entire system. Backup for a cooling water system could be a set of pumps that deliver municipal water to a few crucial portions of the cooling system in the event of a cooling system breakdown. It may not always be possible to provide backup to a utility, but when a failure could lead to an accidental release a backup should be considered.

The second principle of safe utility design is that the loss of a utility in one section of a plant should not result in the loss of that utility to other sections of the plant. Breaking or plugging a utility line in one process unit should not result in the loss of that utility to another area of the plant. This implies parallel rather than series distribution for critical utility systems. Loop piping systems are more effective in meeting this criterion than are branch systems. Complete adherence to this principle will sometimes be difficult to achieve, but it should be attempted whenever possible.

Operability--

Considering the human aspect of process operation and maintenance during the design phase of a project, may help to reduce the potential for an accidental release by enhancing operability of a plant. A plant should be capable of running under manual control long enough to complete a safe shutdown. Automatic process control systems can be expected to fail from time to time. Valves, gages, and other instruments and controls should be located where they are easy to use. Important instruments and controls should be readily distinguishable from less important instruments. Unnecessary complexity should be avoided. An overcontrolled plant may be as difficult to operate as an uncontrolled plant. Operators may bypass control systems that are difficult to maintain or that result in frequent process upsets or interruptions.

Any actions that are essential for safe operations should be set up in a way that minimizes effort to the operator in order to facilitate their implementation. An important task that is difficult to perform may be overlooked or implemented too late. Preventing this kind of error is the responsibility of both management and the design engineer. For example, if water must be regularly drained from a vessel or if samples must be regularly withdrawn, then the drain or sample loop should not be located at the top of a ladder. Important valves should be readily accessible. Movement of personnel from one task to the next should be taken into consideration. For example, people may take the easiest route between two points even if it means inappropriately climbing over equipment.

Unnecessary clutter such as extra piping and equipment can make a process difficult to operate and may increase the potential for an accidental release. Facilities often evolve as modifications and additions are made. Care should be taken to streamline and simplify by removing unnecessary piping and equipment as modifications are made.

Fail-safe Design--

A fail-safe control device is one designed to move to a preset position upon failure of the instrument air or electricity. For example, fail-safe pneumatic control valves are designed to go to the fully open or fully closed position on air failure. The purpose of fail-safe equipment is to reduce the potential for a process upset by preassigning the failure modes for process controls. A correct decision as to whether a device should close or open on failure is essential for safe plant design. For most processes, some type of formal design evaluation procedure, such as a Hazardous and Operability Study (HAZOP) study, may be useful for evaluating what failure mode should be selected.

Fire Prevention and Protection--

A properly designed plant will have fire protection systems external to the process unit, such as sprinklers, as well as inherent fire protection design features. From an accidental release perspective, fire prevention and protection is important because fire damage could lead to an accidental release and because many design considerations associated with fire prevention are actually accidental release prevention measures. Much has been written on fire prevention and protection.

The National Fire Protection Association has issued guidelines in the form of "Flammable and Combustible Liquids Code" (5). Generally, local ordinances will have specific guidelines for fire protection systems. A detailed discussion of the design of fire protection systems such as sprinklers, foams, etc. is outside the scope of this text; however, this section provides an overview of some fire protection design measures.

The supply of fire fighting water and the availability of utilities in the event of a fire is important. In addition to controlling fires, fire-fighting water (and steam) are often used to control the spread of vapors from an accidental release. The loss of utilities to the entire facility because of a fire in one process unit may result in a loss of process control that could end in an accidental release.

The fire fighting water distribution system is important. A loop design rather than a branch layout design may be the best arrangement for water lines in high hazard areas because a loop design ensures water availability even if lines have been cut off in one area of the plant. Valves should be placed throughout the distribution system so that a damaged line can be isolated. These valves may need to be remotely operable.

The primary water supply is usually designed to supply water for fire fighting for at least four hours. All sources combined are usually designed to be able to supply water for an additional two hours (5). Many other features of a fire fighting water system, including specifications on water requirements, pumps and pumping, sprinkler systems, fire extinguishers and other aspects of fire protection, are presented in additional NFPA publications. Specialized fire fighting equipment, such as foams or extra sprinklers or water curtains, should also be considered in highly hazardous areas.

Fireproofing of structural steel, piping, and machinery is often necessary. Fireproofing may include special insulations or materials of construction.

Adequate drainage is important for fire prevention, especially for flammable liquid spills. Flammable solvents may be carried to other locations within a plant on the surface of water. The contents of a drainage trench may ignite and spread fire throughout a plant. Submerged equipment is likely to malfunction and contribute to the hazard. Drains should be sized to handle the maximum anticipated load. The presence of debris such as insulation and tags that may clog drains should be accounted for in the design. To avoid this, trenches sometimes have a cover two thirds closed and one third grate (5). This dampens flames within the trench if a fire occurs. Flame traps are usually spaced periodically throughout a trench to prevent the spread of a fire.

Indoor facilities require additional fire protection. Where flammable dust or vapors may be present, buildings should be constructed with nonload-bearing walls so that walls lost because of an explosion will not result in collapse of the building. In addition to area sprinklers, it may be necessary for each piece of equipment to be protected by a local device. Local flammable gas detectors and/or area monitors are often used and placed near likely release points. Air is handled through ducts in indoor facilities. Flammable dusts, vapors and vapor condensate can collect in these ducts. For this reason, vent and duct systems are specifically designed with safety features such as those suggested in the literature (8).

Fugitive emissions of flammable materials are sometimes controlled by constructing vented enclosures around equipment. Process fittings such as valves or flanges, or process machinery such as pumps or compressors are potential candidates for this type of control. The vent lines from these enclosures are often piped into a common manifold and sent to a treatment device. Air in the vent manifold can lead to fire and explosion. Air leaks into the vent system can be prevented by creating a slight positive pressure with an inert gas. Diluting with an excess of air is another approach to keep the concentration below the flammable or explosive limits. A probe could be installed to monitor oxygen levels in the vent.

Electrical Systems--

Fire hazards are reduced by selecting the appropriate class of electrical equipment. Electrical equipment is given a classification and a division within that classification by the manufacturer which indicates what type of environment the equipment can safely operate in without becoming an ignition source.

Class I equipment is often referred to as "explosion proof" and is the class required where flammable atmospheres may be present. A summary of some locations encountered in a chemical plant and the equipment classification that would apply to each location is specified by the National Fire Protection Association (5). The following definitions of Class I, Divisions 1 and 2, are provided by the National Fire Protection Association:

> Class I, Division 1. A Class I, Division 1 location is a location: 1) in which ignitible concentrations of flammable gases or vapors can exist under normal operating conditions; or 2) in which ignitible concentrations of such gases or vapors may exist frequently because of repair or maintenance operations or because of leakage; or 3) in which breakdown or faulty operation of equipment or processes might release ignitible concentrations of flammable gases or vapors, and might also cause simultaneous failure of electric equipment.
>
> Class I, Division 2. A Class I, Division 2 location is a location: 1) in which volatile flammable liquids or flammable gases are handled, processed, or used, but in which the liquids, vapors, or gases will normally be confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems, or in case of abnormal operation of equipment; or 2) in which ignitible concentrations of gases or vapors are

normally prevented by positive mechanical ventilation, and which might become hazardous through failure or abnormal operation of the ventilating equipment; or 3) that is adjacent to a Class I, Division 1 location, and to which ignitible concentrations of gases or vapors might occasionally be communicated unless such communication is prevented by adequate positive-pressure ventilation from a source of clean air, and effective safeguards against ventilation failure are provided.

It may be appropriate to use Class I equipment exclusively throughout a plant that handles highly toxic chemicals. Ordinary electrical equipment is usually considered acceptable in these locations if it is installed in a room or enclosure maintained under positive pressure by ventilation air that is not contaminated by flammable vapors. If such enclosures are used where toxic chemicals are involved, then it would be appropriate to install an alarm system to sound when the enclosure loses pressure. Additional details may be found in the National Electrical Code, 1984, put out by the National Fire Protection Association (10).

Storage and In-Process Inventories--

The potential effects of an accidental release will be reduced as both storage and in-process inventories of toxic and flammable materials are reduced. No generalized formal methods appear to have been developed for reducing inventories. Each process is unique and potential reductions will be specific for that process.

Reducing the volume of process vessels is probably the most obvious method available for in-process inventory reduction. While it is sometimes possible to reduce the volume of intermediate hold and feed vessels or of process piping in an existing plant, this is best accomplished in the initial design of the plant. A more practical approach for an existing plant is to reduce the volume contained in process vessels rather than to reduce the actual volume of the vessel. Improved process control would assist in this type of volume reduction. Better process control would reduce fluctuations in upstream and downstream processes and allow for a smaller intermediate storage volumes.

Substitution of chemicals or equipment may be used to reduce both storage in-process inventories. Some of these substitutions are practical modifications for an existing plant and some are best considered in the initial plant design. Heat transfer systems are good candidates for substitutions. A flammable heating fluid may be replaced with a nonflammable heating fluid. High temperature unit operations such as distillation may possibly be replaced with lower temperature unit operations such as adsorption, crystallization or liquid-liquid extraction. An example of an equipment substitution is suggested by Lees (1): replace a kettle reboiler with a thermosiphon reboiler. Thermosiphon reboilers hold a smaller inventory than do kettle reboilers.

Altering the process chemistry may reduce inventories. For example, the necessity of storing an intermediate could be eliminated by combining two reactions and running them simultaneously in the same reactor. A more efficient catalyst could reduce reactor residence time and inventory at an equivalent production rate. A non-toxic or nonflammable solvent could be substituted for a flammable or toxic solvent, or it might be possible to eliminate the solvent altogether and run the reaction "neat." It may be possible to substitute a nonflammable or non-toxic raw material for toxic or flammable material. As with all potential inventory reduction methods, some of these alternatives would best be explored in the process development stage and are more easily applied to new rather than existing facilities, but certain changes still might be developed for existing facilities.

Special Safety Requirements--

A hazardous process, or a process that handles toxic or flammable materials may require special safety requirements that were not called for in the previous principles of design. Such features are generally mitigative in nature but may also include the addition of extra preventive or protection measures. Some of these, discussed later in this manual, are scrubbers and flares. Blast shields, water or steam curtains, specialized spill cleanup equipment and specialized release detection equipment and alarm systems are examples of mitigation measures that may be required. Mitigation measures are discussed in the companion manual on mitigation, in this series.

3.3 EQUIPMENT DESIGN CONSIDERATIONS

The equipment in a chemical process may be broadly divided into four categories:

- Vessels;
- Piping (including valves);
- Process Machinery; and
- Process Instrumentation.

This section focuses on some fundamental design considerations, typical failure modes, and control measures for these process equipment categories that are necessary to prevent failures from causing accidental releases. Certain general topics applicable to all equipment are discussed first. These include materials of construction and general equipment failure modes.

3.3.1 Materials of Construction

Selecting the wrong material of construction can lead to equipment failure by corrosion, erosion, or mechanical wear. A variety of process characteristics determine an appropriate material of construction. Process fluid characteristics such as alkalinity, acidity, abrasiveness, and reactivity must be considered in combination with pressure and temperature extremes and the frequency and magnitude of temperature and pressure fluctuations. General procedures for selecting appropriate materials of construction are well defined in the technical literature (11). Even if an appropriate material is specified in the original design, a contractor or vendor may substitute one material for another or maintenance personnel may replace a part with a part made of an inappropriate material. It is valves, flanges, gaskets, bolts or other small parts of a process unit that are likely to be made of an incompatible material. These small substitutions are potentially dangerous because their significance as a potential cause of system failure leading to a release may not be fully appreciated.

An example qualitative guideline for evaluating the appropriateness of a material of construction under acid conditions is presented in Figure 3-1 (11). The graph presents qualitative information on the range of conditions for different materials. The variables include oxidizing environment, reducing environment and chloride content. This chart does not show temperature dependency, which is also an important consideration.

The material strength requirements depend on the temperature and pressure to which a piece of equipment is subjected. Calculation of strength requirements should be based on the anticipated normal operating conditions, extremes, and on the frequency of heating-cooling, pressurization-depressurization cycles that the system will undergo. A detailed discussion of the design specifications that would be required for different conditions is outside the scope of this text, but is fundamental in the field of design and fabrication for vessels and other equipment.

For vessels, piping, pipe fittings and other hardware, design codes or standards are available that define in detail the steps required to properly account for stresses that equipment will experience. These procedures first define specific criteria for establishing the design pressure and temperature. The design conditions are established by taking into account the maximum temperature and pressure that will be experienced under normal operations, and the frequency and severity of occasional excursions from the normal maximum conditions. After the design conditions are set, the standards outline methods for determining wall thickness based on the design temperature and pressure and on forces other than pressure forces that result in torsion, axial compression or tension, and bending. Examples of additional forces are stresses caused by repeated temperature and pressure cycles or stresses caused by the thermal expansion and contraction of piping. An allowance for

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============================================================================================
MATERIAL OF       :                             :                             :
CONSTRUCTION      :    REDUCING ENVIRONMENT     :    OXIDIZING ENVIRONMENT    :
--------------------------------------------------------------------------------------------
                  :                             :                             :
TANTALUM          : XXXXXXXXXXXXXXXXXXXXXXXXXXX : XXXXXXXXXXXXXXXXXXXXXXXXXXX :
ZIRCONIUM         : XXXXXXXXXXXXXXXXXXXXXXXXXXX :                             :
HASTELLOY B-2     :          XXXXXXXXXXXXXXXXXX :                             :
Ti-Pd             :                   XXXXXXXXX : XXXXXXXXXXXXXXXXXXXXXXX     :
TICODE-12         :                      XXXXXX : XXXXXXXXXXXXXXXXXXXXXXXXXXX : CHLORIDES
Ti                :                             :  XXXXXXXXXXXXXXXXXXXXXXXXXX :
HASTELLOY C-4     :                       XXXXX : XXXXXXXXXXXXXXXXXXXXXX      :
MONEL 400         :                       XXX   :                             :
HASTELLOY G       :                           X : XXXXXXXXX                   :
                  :                             :                             :
--------------------------------------------------------------------------------------------
                  :                             :                             :
COPPER ALLOYS     : XXXXXXXXXXXXXXXXXX          :                             :
ALUMINUM          :                             :     XXXXXXXXXXXXXXXXXXXXXXX :
MONEL 400         :     XXXXXXXXXXXXXXXXXX      :                             :
NICKEL 200        :     XXXXXXXXXXXXXXXXXXXXX   :                             :
INCONEL 600       :      XXXXXXXXXXXXXXXXXXXXXX : XX                          :
430 SS            :                             :                   XXXXXXXXX :
304 SS            :                             :     XXXXXXXXXXXXXXXXXXXXXXX :
316 SS            :                             :   XXXXXXXXXXXXXXXXXXXXXXXXX :
CARPENTER 20 Cb-3 :                           X : XXXXXXXXXXXXXXXXXXXXXXXXXXX : NO CHLORIDES
INCOLOY 825       :                        XXXX : XXXXXXXXXXXXXXXXXXXXXX      :
HASTELLOY B-2     : XXXXXXXXXXXXXXXXXXXXXXXXXXX :                             :
HASTELLOY C-4     :              XXXXXXXXXXXXXX : XXXXXXXXXXXXXXXXXXXXXX      :
HASTELLOY G       :                XXXXXXXXXXXX : XXXXXXXXXXXXXXX             :
Ti                :                             :    XXXXXXXXXXXXXXXXXXXXXXXX :
Ti-Pd             :                XXXXXXXXXXXX : XXXXXXXXXXXXXXXXXXXXXXXXXXX :
CAST IRON, STEEL  : XXXXXXXXXXXXXXXXXXXXXXXXXXX :                             :
ZIRCONIUM         :                             : XXXXXXXXXXXXXXXXXXXXXXXXXXX :
                  :                             :                             :
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Figure 3-7. Example guide for material selection under acidic conditions.

corrosion, erosion, or the depth of threads or other grooves must be made by the designer. Such an allowance is necessary since these factors weaken the basic material. An additional allowance is usually provided where toxic chemicals are involved.

The published standards for determining the strength requirements for process equipment should be considered minimum standards where toxic chemicals are involved. These standards are general and cannot cover all possible design, construction, and operating conditions. For example, standards cannot account for unrelieved stresses created during fabrication or installation. The equipment designer of a facility that handles toxic chemicals should try to account for all stresses and allow a safety factor consistent with the hazards involved.

At high pressures, over 3000 psig, special designs not necessarily covered by design standards or codes are sometimes used. For example, at such pressures, a vessel constructed from ordinary low-carbon-steel plate would become too thick for practical fabrication by ordinary methods. The alternatives are to make the vessel of high-strength plate, use a solid forging, or use multilayer construction. Such specialized fabrication methods may not be subject to any particular standards or codes.

Very low or high temperature operations also require special consideration. These extremes are more a problem of material selection than they are of material strength requirements (though one is closely related to the other). Brittle fracture is possible wherever very low temperatures are involved. The materials used in plants handling low temperature fluids should have a ductile/brittle transition temperature below not only the normal operating temperature but also below the minimum temperature that may be expected to occur under abnormal conditions. Brittle fractures are serious since the fracture can propagate at a velocity close to that of sound. For high temperatures a lining is often used to protect the outer equipment from the high temperatures. A specialized lining must be placed inside a vessel of special construction when high temperatures and pressures are involved.

3.3.2 General Equipment Failure Modes

A number of failure modes are common to all categories of equipment, and each of the three fundamental equipment categories of vessels, piping, and process machinery have failure modes to which they are especially susceptible. This subsection presents a general discussion of potential failure modes and is a basis for the discussions specific for each of the equipment categories presented in later subsections.

Categories of failure modes that may lead to an accidental release are:

- Process upset causing pressure or temperature to exceed design limits of the equipment;
- Faulty fabrication;
- Faulty repair or installation;
- Corrosion;
- Erosion; and
- Mechanical failure.

Process Upsets--

A process upset, as meant here, is any event that leads to a loss of process control that could result in an accidental release. A runaway reaction and overpressure, an internal explosion, or even failure caused by an external explosion in an adjacent process or storage unit would all be examples of process upset failures. Thus a failure occurring as a result of a fire would also be a process upset failure. Numerous events, including instrument failure, operator failure, or mechanical failure, can result in a loss of process control. Process upsets, which can lead to equipment failure, were discussed in Section 2 of this manual on Process Design Considerations.

Faulty Fabrication--

An equipment failure could result from faulty fabrication. A poor weld would be an example of a fabrication fault. Incomplete penetration, lack of fusion, or a porous weld could result from improper or careless welding techniques. Improper heat treatment of a metal component can result in unrelieved stresses. As will be discussed latter, these stresses can contribute to several forms of structural failure. Poor dimensional tolerances can result in excess mechanical stress or poor fit at gasketed joints. The use of an improper material of construction can result in premature corrosion and failure. Additionally, attempted cost saving steps such as substituting one grade of equipment for a lower grade can result in premature equipment failure. Detailed consideration of fabrication faults is beyond the scope of this manual, but there is a voluminous literature on the subject (e.g., 13).

Faulty Repair or Installation--

Another contributor to equipment failure can be faulty repair or installation. One author believes that most initial process plant designs are relatively safe but that problems arise because changes, substitutions or mistakes are made during the initial construction of the plant (14).

Corrosion--

The materials of construction in a chemical plant are subject to a number of types of corrosion. Corrosion can structurally weaken equipment to the point of failure under either normal process operating conditions or process upset conditions.

There are numerous categories of corrosion. Some of these are (1):

1) General corrosion,
2) Scaling,
3) Exfoliation,

4) Intergranular corrosion,
5) Stress-related corrosion,
    a) stress corrosion cracking,
    b) corrosion fatigue,
    c) stress-enhanced corrosion,
6) Galvanic corrosion,
7) Corrosion pitting,
8) Knife-line corrosion,
9) Crevice corrosion,
10) External corrosion.

These are all discussed in the cited reference. Some categories are discussed further below.

Stress corrosion cracking is the brittle failure of normally ductile metals that occurs under the combination of corrosion and tensile stress. The stress may be internal or external. The American Petroleum Institute states that almost any alloy can be made to fail by a stress corrosion cracking mechanism (15). Caustic embrittlement is a common form of stress corrosion cracking, as is the well known chloride stress corrosion cracking of stainless steels.

Intergranular corrosion occurs when austenitic steels are heated in the temperature range of 750 to 1650°F, or cooled through this range. A complex carbide precipitates out and collects along grain boundaries. These pockets of carbide are susceptible to corrosion by relatively mild aqueous corrodants. The end result of this type of corrosion is the formation of cracks.

Galvanic corrosion is used to describe an accelerated electrochemical type of corrosion that occurs when two different metals are in contact with each other in the presence of an electrically conductive solution such as an aqueous salt or acid solution. An electrical current flows between the two metals and rapidly corrodes the metal that acts as the anode.

Other general categories of corrosion include graphitic corrosion, dezincification and biological corrosion. Many additional chemical-specific varieties of corrosion are possible. Discussions of corrosion are numerous in the technical literature (16,17,18).

Erosion--

Erosion is the physical wearing away of process equipment materials by the abrasive action of rapidly moving liquids, gases, or solids. Erosion can result in an equipment failure because of physical weakening. The rate of erosion is a function of the velocity of the process stream, the angle of impingement upon the surface of concern, the solids concentration of the stream and the temperature of the stream. Erosion and corrosion may sometimes occur together. Some materials form a layer of corrosion that acts as a barrier to further corrosion. These protective layers usually have less physical strength than the material on which they are formed. If erosion destroys this layer, then the surface of the material will be eroded away as new corrosion layers are formed and eroded off. A common site of erosion is in the bends of piping.

Mechanical Failure--

Mechanical failure of equipment results from overstress, whether internal or external. Extremes or cycles of temperature and pressure can result in mechanical failure of process equipment. Externally applied stresses such as vibration and supported loads can also result in the mechanical failure of process equipment.

Creep is the flow of metals held for long periods of time at stresses lower than the normal yield strength. Stress rupture is the failure of a metal at stresses lower than the normal yield strength after it has reached a point beyond which it cannot creep.

Repeated heating and cooling cycles may sometimes result in thermal fatigue. Thermal fatigue produces cracks and may ultimately result in a structural failure. A sudden change in temperature can sometimes result in thermal shock. Thermal shock which causes the sudden unequal expansion or contraction of different parts of a piece of equipment, can result in cracking or separation.

Vibration can be very destructive. Metals can become fatigued and fail in a manner similar to that of thermal fatigue. Concrete foundations can be destroyed by vibrating equipment. The weight of insufficiently supported equipment or the stress caused by settling foundations or supports is also destructive.

The ensuing subsections discuss some of the design considerations, failure modes, and control technologies specific to each of the previously named equipment categories: vessels, piping, and process machinery.

3.3.3 Vessels

As used here, vessels include all major items of equipment containing significant inventories of liquids or gases; this includes both process and storage equipment. Vessels include tanks, reactors, heat exchanger shells, receivers, columns, and similar equipment. Vessels may be atmospheric, pressurized, or operate under vacuum.

Vessel equipment failures that could result in an accidental release could occur in one of the following locations:

- Piping joints at vessel nozzles;
- Vessel seams, including welded attachments such as nozzles and support lugs;
- Vessel shell wall failure; and

- Vessel flanged joints such as where a head joins the shell.

Vessel Pipe Joint Failure--

Joints of piping to vessels are either threaded, flanged, or welded, although flanged joints are probably the most common for larger process vessels with connections over two inches. Faulty installation or repair may be the most common causes of failure at a flanged attachment. Incorrect gaskets may be used. Flanges may be bent by excessive bolt tightening, which results in insufficient pressure on the gasket to assure a complete seal. Gasket faces may be scratched or dented. A gasketed joint may be bolted with the gasket half in the grove and half out. Mechanical stress due to inadequately supported loads or vibrations may overstress bolts and result in a leak. The bolts around the perimeter of a gasketed joint often require a specific tightening sequence at a specific tightening torque. A failure to follow these specifications can result in a poor seal. Flanges or bolts of incorrect specifications may be substituted during a repair, but substitutions of this kind could result in a premature failure of the flanged joint.

Flanged or threaded joints are sometimes used to join equipment and piping of different materials of construction. A joint of this type is potentially subject to galvanic corrosion. The threads on a threaded attachment can be destroyed by galvanic corrosion, resulting in a complete failure of the joint.

Vessel Seam--

Generally, two types of seams are used on vessels: welded and riveted. Riveted vessels are not recommended for use with toxic chemicals because the overlap at a riveted seam is subject to both internal and external corrosion and each rivet is the potential source of a leak due to corrosion. Stresses can be concentrated around each rivet and stress or stress corrosion cracks can form around rivets. Vessels for toxic chemicals should have welded seams, but even these may fail under certain circumstances.

With vessel seams, the primary preventive measure is proper initial welding. Sloppy welding may result in a porous or incomplete weld that does not provide the necessary structural strength. Also, a welded seam may leak because of corrosion. The metal surrounding a weld is heated during the welding process, and this heating can result in unrelieved stress in the metal which may contribute to the formation of stress corrosion cracking. Heating can also create the precipitation of complex carbides, which can result in intergranular corrosion.

Sometimes welding is used to join two different metals. This type of weld is subject to thermal fatigue when it is subjected to repeated heating and cooling cycles caused by differential expansion and contraction of the different metals. Cracks from thermal fatigue will initially form slowly but will progress more rapidly with time.

Some welds are actually designed to fail in the event of an overpressure. An atmospheric storage vessel will often be designed to fail at the shell-to-head joint to prevent the entire contents of the tank from emptying.

Vessel Shell Failure--

The nozzles attached to a vessel shell are sites for potential vessel failure. Inadequately supported loads on fittings connected to a nozzle may result in failure of the nozzle. Thermal expansion and contraction of piping may create excessive stress on a nozzle. A tank settling under subsidence of the ground beneath it can cause connection and nozzle failure. Vibration of support piping or equipment may also cause a nozzle failure. Unrelieved stress formed during fabrication may contribute to stress corrosion cracking. Galvanic corrosion is a potential wherever a fitting made of a different metal is attached to a nozzle.

External forces may cause the main vessel shell to be susceptible to failure. Unsupported loads such as support piping, platforms or walkways can cause the collapse of a vessel shell. Loads created by foundation settling can also cause a vessel shell to collapse.

Thermal shock caused by a rapid temperature swing will result in unequal expansion or contraction of different parts of a vessel, which may result in damage. Thick walled vessels are more susceptible to cracking due to thermal shock than are thin walled vessels. Some vessel coatings may pull loose and fittings may pull away because of thermal shock. A vessel shell (particularly around a nozzle) may crack because of repeated heating and cooling cycles. The effect is similar to thermal shock except that the fatigue of the metals and of the joints between different metals develops more slowly.

A vessel shell is subject to several types of corrosion. Corrosion in the plate body of the shell, as opposed to seam welds, can result in thinning of the wall and cracks which lead to shell plate failure. A bottom plate in contact with a pad is particularly susceptible to external corrosion. An insulated vessel may be subject to external corrosion in situations where moisture has soaked into insulation and is trapped next to the vessel. A vessel head is susceptible to corrosion that accompanies evaporation and condensation of trace quantities of water. Numerous additional varieties of corrosion specific to the chemicals and materials of construction are possible.

Vessel Failure Prevention Controls--

The primary prevention control for vessel failure related to the equipment itself is proper design and construction and the avoidance of the kinds of conditions, discussed above, that can lead to failure. The ASME Boiler and Pressure Vessel Code, which specifies design standards for boilers, and pressure vessels, was referred to in Subsection 3.2 of this manual. Most states have incorporated all or part of the Code into their legal requirements. Where toxic chemicals are involved, it may be appropriate to use the ASME Code as a minimum standard for the design of vessels. This may not be practical for large storage vessels, however, where at a minimum, design might be according to API (19,20,21). For all vessels, more stringent design may be appropriate than these minimum standards where toxic chemicals are involved.

Most processing vessels are designed in accordance with ASME Code Section VIII, Division 1. Subsection B of Section VIII provides some specific instructions for the fabrication of vessels used in "lethal service," which is defined as a vessel used to handle poisonous gases or liquids of such a nature that a very small amount of the gas or of the vapor of the liquid mixed or unmixed with air is dangerous to life when inhaled. The Code specifies that all vessels in lethal service shall have all butt-welded joints. These joints must be fully radiographed to test their integrity before use. All vessels made of carbon or low-alloy steel shall be postweld-heat-treated. The ASME Code stipulates that brazed vessels cannot be used in lethal service. In general, butt-welded or flanged joints should be used throughout a process handling hazardous materials. Threaded or riveted joints should be avoided.

A storage vessel usually has less strength than a process vessel (such as a reactor). For example large atmospheric storage vessels are often designed to withstand only 8 inches of water and will burst at about three times this pressure. These same vessels can only tolerate about 2.5 inches of vacuum. Because they are easy to rupture or collapse, this type of tank may not be suitable for storing large quantities of toxic chemicals. Care must be taken when sizing vents and inlet and outlet lines on these vessels. The vent should be sized to accommodate the maximum possible flowrates into and out of the vessel. To prevent an overflow from overpressuring the tank, the vent line and overflow lines must not rise more than eight inches above the side of the vessel. Rapid heating or cooling of these vessels can cause a rupture or collapse due to expansion or contraction in the vapor space.

Other storage vessel designs commonly used in the chemical industry may not be appropriate for storing toxic chemicals. For example, because of vapor loss, external floating roof tanks are probably not appropriate.

The American Petroleum Institute has stated that corrosion is the prime cause of deterioration in vessels (14). Because this deterioration is often slow, it may go undetected. The primary defense against corrosion is the selection of the correct materials of construction. Very rarely will a material be completely resistant to corrosion where it is being used. In most cases, an allowance for corrosion is provided by increasing the thickness of the material.

Protective coatings are often used to slow the rate of corrosion. These coatings should be used with care when hazardous materials are involved. Very thin coatings (less than 0.75 mm thick) should not be relied on for corrosion protection because coatings of this thickness may have very small flaws that will allow material to contact the surface below the coating (3). Most coatings are permeable to some chemicals. When a coated material is used, it should be resistant to all components to which it will be exposed. If a coating is permeable to some species in a mixture, then this species will penetrate the coating and contact the surface below. Even if the permeable species is not corrosive to this surface it may damage the bond between the coating and the support surface and ultimately result in a failure of the coating.

Vessels should be constructed to minimize crevices and allow for complete drainage, cleaning, and easy inspection. The internals of a vessel should be so arranged that all exposed surfaces can be cleaned and so that liquid is not held up when the vessel is emptied. External corrosion can be reduced by protecting all outer surfaces with a coating. If insulation is used, care must be taken to seal the insulation so that moisture does not get in and become trapped against the vessel wall.

Care must be taken when dissimilar metals must be contacted with each other as galvanic corrosion can result. The degree to which galvanic corrosion will occur will depend on the metals involved, on the area of contact, and on the electrolytic character of the liquid contacting the metals. Table

3-4 shows the Galvanic Series of Metals and Alloys. The farther apart two metals appear on this table, the more susceptible to galvanic corrosion they will be when in contact with each other. The American Petroleum Institute has compiled a list of design recommendations to combat galvanic corrosion (21):

- Select combinations of metals as close together as possible in the galvanic series.

- Avoid making combinations where the area of the less noble material is relatively small. It is good practice to use the more noble metals for fastenings or for other small parts in equipment built largely of less resistant material.

- Insulate dissimilar metals wherever practical. If complete insulation cannot be achieved, materials such as paint or plastic coatings at joints will help to increase the resistances of the circuit.

- Apply coatings with caution. For example, do not paint the less noble material without also coating the more noble, otherwise greatly accelerated attack may be concentrated at imperfections in coatings on the less noble metal. Keep such coatings in good repair.

- In cases where the metals cannot be painted and are connected by a conductor external to the liquid, increase the electrical resistance of the liquid path by designing the equipment to keep the metals as far apart as possible.

- If practical, add suitable chemical inhibitors to the corrosive solution.

TABLE 3-4. GALVANIC SERIES OF METALS AND ALLOYS

Corroded end (anodic, or least noble)

Magnesium
Magnesium alloys
Zinc
Aluminum alloys
Aluminum
Alclad
Cadmium
Mild steel
Cast iron
Ni-Resist
13% chromium stainless (active)
50-50 lead-tin solder
18-8 stainless type 304 (active)
18-8-3 stainless type 316 (active)
Lead
Tin
Muntz metal
Naval brass
Nickel (active)
Inconel 600 (active)
Yellow brass
Admiralty brass
Aluminum bronze
Red brass
Copper
Silicon bronze
70-30 cupronickel
Nickel (passive)
Inconel 600 (passive)
Monel 400
18-8 stainless type 304 (passive)
18-8-3 stainless type 316 (passive)
Silver
Graphite
Gold
Platinum

Protected end (cathodic, or most noble)

Source: Reference 3.

- If dissimilar materials well apart in the series must be used, avoid joining them by threaded connections, since the threads will probably deteriorate excessively. Welded joints are preferred, and the use of filler material more noble than at least one of the metals to be joined.

- If possible, install relatively small replaceable sections of the less noble material at joints, and increase its thickness in such regions. For example, extra-heavy wall nipples can often be used in piping, or replaceable pieces of the less noble material can be attached in the vicinity of the galvanic contact.

- Install pieces (sacrificial anodes) of bare zinc, magnesium, or steel to provide a counteracting effect that will suppress galvanic corrosion.

Control Effectiveness--

The control effectiveness of various vessel design factors is measured in terms of the reliability of vessel components. Some reliability data related to vessels are summarized in Table 3-5. The overall reliability of multicomponent control measures depends on the reliability of the individual components and on the specific design or procedure.

Costs--

Costs for each vessel control measure are summarized in Table 3-6, which lists vessel hazards, corresponding control technologies, and both typical capital and total annual costs associated with each control measure. Costs are in 1986 dollars. Table 3-7 presents design bases for the costs.

Case Examples (1)--

A cylindrical LNG storage tank ruptured and discharged its entire contents over the plant and nearby areas. The LNG vapor ignited and an intense

TABLE 3-5. TYPICAL FAILURE RATES FOR VESSEL COMPONENTS

Component	Failure Rate (Failures/Year)
Vessel shell	
Complete failure	3×10^{-6}
Rupture equivalent to 6 inch opening	7×10^{-6}
Flanged head joint	N/A
Flanged nozzle piping connections, flange leak or rupture	0.0026
Seam welds	N/A

Source: Adapted from References 1, 23 and 24.

TABLE 3-6. VESSEL HAZARDS AND CONTROL TECHNOLOGIES

Basis: Costs represent incremental costs over the baseline system presented in Table 3-7.

Hazard	Control Technology	(1986 Dollars) Capital Cost ($)	Total Annual Cost ($/Yr)
General Failure	Corrosion resistant materials.	30,000	5,200
	Higher pressure rating.	16,000	2,800
	Greater corrosion allowance.	6,000	1,100
	Vibration control in attached piping systems, and on agitators.	630	55
	Extra heavy foundations and extra support structures.	1,500	280
	Fire protection.	$6.60/ft^2$	$0.60/ft^2$
	Increased inspection frequency.	--	800
	Pressure/temperature cycling control.	9,500	1,400
	Adequate pressure relief.	600	50
	Protection from external physical damage (curbing or barrier).	6.00/ft	0.50/ft
Flanged Joint Failure	Correct flange/gasket combinations for intended service.	--	320
	Full diameter, correctly torqued, and full circle bolting.	--	320
	Leak monitoring.	--	1,000
Welded Joint or Seam Failure	Correct weld type and materials.	--	320
	Correct weld procedure.	--	320
Vessel Wall Rupture	Double-walled vessel.	17,000	3,000
	Wall thickness testing.	--	1,200

Source: Adapted from references 25, 26 and 27.

TABLE 3-7. DESIGN BASES FOR VESSEL CONTROLS

Vessel baseline - 10,000 gallon carbon steel pressure, storage vessel, 50 psig rating, ellipitical heads.

Increased corrosion resistance - same as vessel baseline except 316 stainless steel.

Higher pressure rating - same as vessel baseline except 100 psig rating.

Greater corrosion allowance - same as vessel baseline except 1/8" thicker wall and heads.

Vibration control for attached piping - assume increase in piping supports from one per 14 ft. to one every 7 ft. for 100 ft. of pipeline, 4 inch pipe.

Extra heavy foundations and extra support structures - Assume 50% increase in cost over that required for baseline vessel, where cost for the vessel is assumed to be 10% of the baseline vessel allowed, without any peripheral equipment.

Fire protection - Assume the addition of a water deluge system over the baseline vessels.

Increased inspection frequency - Assume an increase of 40 hours per year at an hourly total labor cost of $20/hour.

Pressure/temperature cycling control - Assume the installation of a better control loop somewhere in the process unit of which the vessel is a part. Assume a conventional control loop.

Adequate pressure relief - Assume the addition of a 4-inch rupture disk to the vessel. The baseline vessel is assumed to already have a safety relief valve.

Protection from external physical damage - Assume the addition of vehicle curbing around the vessel process area.

Correct flange/gasket combination - Assume increased supervisory labor at 8 hours per year and $40 per hour.

Full diameter, correctly torqued bolts, and full circle bolting - Assume increased supervisory labor at 8 hours per year and $40 per hour.

Leak monitoring - Assume monitoring costs as primarily labor at an extra 40 hours per year at $25 per hour.

Correct weld type, materials, and procedure - Assume increased supervisory labor at 8 hours per year and $40 per hour.

(Continued)

TABLE 3-7 (Continued)

Double-walled vessel - Same basic specification as baseline vessel except with double wall allowing for space between inner and outer wall.

Wall thickness testing - Assume inspection labor requirement at 40 hours per year and $30 per hour.

fire burned at the plant, causing great loss of life and extensive damage. More LNG flowed from the plant as liquid down the storm sewers, where it mixed with air and exploded. Though the cause of the ruptures is uncertain, an investigation concluded that the low carbon steel used in the vessel construction may have been unsuitable and that failure may have been caused by vibration or seismic shock. The final death toll was 128 and the number of injured was estimated to be between 200 and 400.

In another incident, an estimated 30 tons of ammonia escaped from a ruptured anhydrous ammonia storage tank. A gas cloud 492 feet in diameter and 66 feet deep formed, killing 18 people both inside and outside the plant. The cause of the failure was brittle fracture of the dished end of the tank. Evidence suggested there had been no overpressure or overtemperature of the tank contents, and no other triggering event was determined. Ultrasonic investigation of the dished end of the tank revealed numerous subsurface fissures, perhaps caused by progressive cold-forming of the dished end.

3.3.4 Piping

The term "piping" is used here to describe three closely associated categories of equipment: piping, fittings and valves. Piping can be drawn, rolled and welded, or cast. Fittings are used to connect various pipe sections or connect pipe to another piece of equipment, to change the direction of flow, or to provide a branch. Valves are used to regulate the flowrate or direction of flow through lines. Valves use a number of different mechanism to regulate flow. Some common varieties include, ball valves, gate valves, globe valves, plug valves, diaphragm valves, butterfly valves, and check valves. Check valves as a control technology for preventing backflow have been discussed in Section 2 of this manual. Materials of construction for all of these devices commonly include both metals and plastics.

Piping failures may occur at the following locations:

- Piping wall (including fittings);

- Joints;

- Valve stems;

- Valve bodies;

- Internal valve mechanisms; and

- A hose or hose connections.

Pipe Wall Failure--

Piping can be drawn, rolled and welded, or cast. Welded piping is fabricated with a welded seam running the length of the pipe. Welded seams are subject to stress corrosion cracking, intergranular corrosion and defective welds, which can cause a pipe wall failure. For toxic chemicals, seamless rather than welded piping is preferable.

A pipe wall is subject to the same failure modes as a vessel shell, including excessive stress. Piping can be subjected to excessive stress by:

- Vibration;

- Misalignment; or

- Thermal expansion and contraction.

Vibration can be a very destructive force to process piping. For example, 18-8 stainless piping subjected to a stress of 30,000 psi at a peak deflection failed after approximately one million cycles. This same pipe subjected to a vibration frequency of 60 cycles/sec. failed from fatigue in five hours (26). Causes of vibration include periodic mechanical motion, pressure pulsation associated with reciprocating machinery, high-pressure drop across a control valve or unstable two-phase flow conditions.

Misalignment of pipe may result in failure by fatigue or in the formation of stress corrosion cracking. Misalignment may be caused by an error in installation of by shifting equipment. Sometimes during construction, two piping ends come together and are not completely in line. These out of line ends are usually forced into position. Forcing the pipes into position will subject them to a stress probably unanticipated in the original design specifications. This unanticipated stress can result in premature pipe failure. Even if the initial installation was done correctly, equipment can settle or poorly placed foundations and stress a pipe run in the same way as would a misaligned pipe. Broken or defective anchors and hangers can create stresses on a pipe run that can result in premature failure of the pipe.

Thermal expansion and contraction that is not properly accounted for in the initial design can cause internal stress. Even if the original design provided for thermal expansion, broken or defective sliding saddles or rollers could cause excess stress during expansion and contraction. In addition to stress caused by thermal expansion, repeated thermal temperature cycles can result in failure caused by thermal fatigue.

Piping is often insulated. Moisture can get trapped beneath the insulation and cause external corrosion. Piping will be particularly susceptible to this near joints and fittings where it is difficult to ensure a good seal for the insulation. The potential problem of atmospheric corrosion under insulation applies for all insulated equipment. It is discussed here under process piping because piping systems are often complex and it is difficult to monitor all portions of the piping system for corrosion problems.

Pipe Joint Failure--

Some of the potential failure modes for pipe joints were discussed in Subsection 3.3.4 on vessels.

Most flanges are attached to the end of a pipe in the form of a flanged-end fitting (a few varieties of pipe may be purchased as flanged-end pipe). Some types of flanged-end fittings have a weaker tolerance for cyclic stress loads than the piping to which they are joined. These varieties include slip-on, socket-welded, and lap-joint flanges. Subjecting these flanges to cyclic stresses may cause an unanticipated failure. Flanges may fail as a result of thermal shock. Flanges must be made of a heavier gage of metal than the surrounding pipe because they may be more susceptible to thermal shock cracking than the surrounding pipe. Selecting flange bolts with inappropriate strength and corrosion resistance can lead to a flanged joint failure.

Pipes can be joined by welding. One variety of welded joint is the socket-weld joint, which cannot resist bending stress as well as the pipe which it joins. This joint may fail prematurely under bending stresses. Additionally, a crevice between the two pipe ends is formed in a socket-weld joint. Liquid can enter this crevice and result in corrosion. A second variety of welded joint is the butt-weld joint. For most types of piping, this joint is as strong as the pipe to which it is joined and may, therefore, be preferred for toxic chemicals. The exception is where a butt-weld joint is used to connect work-hardened pipes annealed by the welding (3). All varieties of welded pipe can fail because of sloppy welding.

A threaded joint can be used to connect pipe sections. A threaded joint is not as strong and resistant to fatigue as the pipe it is joining. Threaded joints have other disadvantages. Turbulence will form at the contraction caused by a threaded joint. This turbulence can contribute to corrosion at a point where the pipe is already thinned by threading. A threaded joint may keep its seal even after most of the threads or pipe wall are destroyed. Such a joint may fail completely before any leakage occurs and before any external decay is detected. Threaded joints can be crushed by the force of the pipe wrench used to tighten the joint, which will weaken the connection and possibly result in later failure. A threaded joint can loosen when subjected to torque. Such torque could be caused by thermal expansion or contraction or by shifting equipment. A loosened joint may not seal completely and may not have as much resistance to stress as a tight joint.

Valve Stem Failure--

A common source of leaks in a piping system is valve stems. Most valves are constructed with some type of packing material around the valve stem that allows the valve stem to rotate while preventing the process fluid from escaping around the stem. Exceptions are diaphragm valves where the process liquid is separated from the stem by the diaphragm and ball valves where face seals are used. Valve packings are made of a number of materials including plastics, metals, and metal composites. Because the valve packing experiences wear every time the valve is opened or closed, it is usually the weakest point of the piping system and will be the first point to fail in the event of an overpressure.

Leaks around a valve stem are frequent but are rarely serious unless the leak results in a fire or explosion. It is possible to tighten the packing to stop a leak when the valve is in operation. However, the life of valve packing and the number of times that the packing can be compressed is limited, requiring periodic replacement. A valve packing failure on a very large valve might be sufficient to discharge a significant amount of toxic chemical, but in most cases a release from a valve steam blowout would not be catastrophic. Leakage around valve stems could indirectly lead to major equipment or process failures, however. For example, small amounts of leakage over a long period of time could result in corrosion that makes the valve inoperable. Such a failure at a critical time in a critical line could lead to a major equipment or process failure.

Valve Body Failure--

The failure of a valve body would be comparable to a pipe failure, and could occur for the same reasons; excessive stress, corrosion or erosion.

The effect of excessive stress is of special concern with valves. Valve bodies are constructed in irregular shapes that may not withstand bending or twisting stresses. Where valves consist of two or more pieces forming a body, the seal between the parts is a weak point, especially if the assembly bolts are improperly tightened. Overstressing could also occur in the body parts themselves if not joined properly to the piping. A valve that is rapidly closed will experience a tremendous surge in pressure. This surge is known as a "water-hammer" or "hammer blow." This surge in pressure can result in failure because of overpressure of the valve body, of the pipe-to-valve fittings, or of the pipe near the valve.

Since valves disrupt the fluid flow, considerable turbulence occurs, which can contribute to erosion.

Internal Valve Mechanism Failure--

The potential cause of failure of an internal valve mechanism depends on the type of valve. Basic types include:

- Gate valves;
- Globe valves;
- Plug valves or cocks;
- Ball valves;
- Diaphragm valves; and
- Check valves.

A failure of the internal valve mechanism can result in low flow or excess flow with all their attendant hazards (see Section 2 of this manual).

A gate valve is composed of a body containing a gate that interrupts the flow. The valve is normally used in the fully open or fully closed positions. Gate valves must usually be constructed of metals, which could limit their usefulness in some corrosive environments.

When handling high-velocity flow of dense fluids, the gate assemblies can shake violently. This vibration can result in failure of the gate assembly, the valve body or the attached piping and equipment. Gates have been known to fall off gate valve stems (27).

Some portion of the stem on a gate valve must be exposed to the process fluid. For some varieties the threaded portion of the stem is exposed. This could result in corrosion or erosion of the stem. Liquid entering the bonnet of this valve when it is opened can be trapped in the bonnet when the valve is closed. Thermal expansion or contraction could rupture the bonnet.

Globe valves are commonly used to regulate fluid flow. The valve is composed of a disk (or plug) that moves axially to seat in the valve body. These valves have a large pressure drop and can be the source of vibrations. In most designs the disk is free to rotate on the stems, which prevents galling between the disk and the seat. However, the ability to rotate can result in a tilted and misaligned disk on closure and the disk on a globe valve can detach from the stem. Process fluid solids, scaling, or corrosion of the seat of disk can result in an inadequate seal.

A plug valve is composed of a tapered or cylindrical plug fitted snugly into a seat in the valve body. When in the open position, the plug has an opening in line with the flow openings in the valve body. A plug valve can be constructed from metals, coated metals, or plastics.

The surface area between the plug and the valve body is large, which can make the plug difficult to rotate. Some types of plug valves use a lubricant to act as a seal and to allow the plug to be more easily rotated. A common way these valves can fail is by seizure of the plug. Temperatures above 500° can cause differential expansion between the plug and the body and result in seizure. A loss of lubrication between the plug and body can result in seizure. Seizure of the valve could contribute to an accidental release if the inability to open or close the valve results in a loss of control of the process. An opposite problem is that a small plug valve could vibrate open or shut if the fit between the plug and valve body became too loose (through wear, for example).

Plug valves can trap a small quantity of the process fluid in the plug cavity whenever the valve is closed. If the process fluid has a high coefficient of thermal expansion, this trapped fluid could result in a ruptured valve if it were heated. An example of such a fluid is liquid chlorine. Since water expands as it freezes, this could also occur with water that is frozen when trapped in the valve. Some valves have a bypass built into the plug, which relieves the plug cavity to the high pressure side of the valve when it is closed. As long as the relief bypass does not become plugged, these valves solve the fluid expansion problem. These valves are unidirectional and are likely to leak if installed backwards.

A ball valve is similar to a plug valve except the plug is in the shape of a ball. Plastic seats are used to seal the ball. Though not as prone to seizure as plug valves, ball valves can seize as a result of thermal expansion, corrosion or fouling. The ability of a ball valve to seal depends on the performance of the plastic seals. Thus, once these seals are damaged or worn, the valve could fail to function properly. Ball valves are usually constructed of metals, which could limit their usefulness in some corrosive environments. A ball valve also has the same disadvantage as a plug valve in trapping process material in the ball when the valve is closed. Again, unidirectional ball valves are available with a vent from the ball cavity to the upstream side of the valve to prevent liquid entrapment.

A diaphragm valve is usually a packless valve composed of a diaphragm made of a flexible material which functions as both a closure and a seal. A compressor mechanism closes the valve by forcing the diaphragm against a seat. Failure of the diaphragm can result in the leakage of the process fluid around the stem, since some varieties of diaphragm valves have no packing around the stem. A diaphragm rupture in a packless valve could result in a significant release of a toxic chemical.

A butterfly valve is composed of a disc mounted on a stem in the flow path. A 90 degree turn of the stem changes the valve from closed to completely open. The butterfly valve forms a complete seal around the perimeter of the pipe. However, minor corrosion or erosion of the disk and seal may cause them to not seal properly. The presence of solid deposits around the sealing surface also may prevent a tight seal upon closure.

A number of varieties of check valves are available. Common varieties include swing, lift (piston check or ball check), tilting-disk or spring-loaded wafer-type check valves. Check valves are also discussed under backflow prevention in Section 2 of this manual.

The common varieties of check valves vary slightly in their mode of action; however, they all incorporate certain common features necessary for their performance.

Successful function of all check valves depends on a reliable seal. The two surfaces that form the seal must remain clean and smooth. The sealing surfaces could be marred by corrosion, erosion, and solids in the fluid stream that could lodge between the sealing surfaces and prevent a complete seal. The portions of a check valve that form the seal have a coefficient of thermal expansion typically 24 to 45 % greater then that of cast or forged carbon steel (4). This could cause unequal thermal expansion of portions of the valve and prevent a tight seal.

All common varieties of check valves have moving parts that must remain flexible and function under the influence of slight pressure changes. Corrosion, solids in the fluid stream, or formation of scale or polymer buildup could prevent these moving parts from operating correctly. Corrosion could also weaken springs and prevent valve closure.

Hoses and Hose Fittings--

Hoses are a frequent source of leaks and may result in large releases.. Two common causes of hose failure are physical wear and poor connections. Because hoses are usually applied for intermittent use or quick connection, a release can result from an incorrectly attached hose. Threaded hoses could be incorrectly secured by only a few threads, by different thread types incorrectly combined, or by the attachment made with a gasket missing.

A release could result from the use of a hose-to-end connection that is not strong enough. An example would be the use of a clamp or metal compression band connection of the type used to attach automobile hoses. These are not suitable for use with toxic materials.

An operating error could result in an accidental release from a hose that is disconnected before the line is properly isolated from the process.

Release Prevention Controls for Piping--

The American National Standards Institute has published standards for chemical plant piping. ANSI standard B31.3 applies to most of the piping that would be present at a facility handling hazardous chemicals. The standards prescribe minimum requirements for the materials of construction, design, fabrication, assembly, support, erection, examination, inspection, and testing of piping systems subject to pressure or vacuum.

Where possible, seamless piping should be used for hazardous chemicals. All joints should be either welded or flanged and threaded joints and fittings avoided. As far as possible, all joints should be butt-welded. Properly done, this provides joint strength equivalent to the original pipe. Flanges should be used only where a removable joint is necessary. If a threaded joint or fitting must be used, then it should be seal-welded. Because of their superior strength, welding-neck flanges may be preferred over other kinds of flanges. An exception must be made for some kinds of coated or specialty piping that can only use lap-joint flanges. The potential for cyclic stresses should be considered when an alternate kind of flange (other than welding-neck) is used. Flange bolts must be consistent in strength and material of construction with the design requirements of the system.

Metal-polyfluorinated ethylenes and metal-graphite spiral-wound gaskets should be used instead of metal-asbestos gaskets where hazardous chemicals are involved. These gaskets will often provide a better seal than the metal-asbestos type. A metal-ring-joint facing may sometimes be preferred over a conventional gasket. In the event of a fire, this type of seal is less likely to leak. The sealing surface is less likely to be damaged in handling than a conventional gasketed seal. The metal-ring-joint facing can be more resistant to the fluid being handled than a conventional gasket. This type of seal is more difficult to disassemble because the flanges can be separated only in the axial direction.

As shown in the previous sections, stress is a common failure mode for all portions of a piping system. The potential for stress-related failures can be reduced by proper design. Some considerations are:

- Shorten connections to reduce bending moment and raise the fundamental frequency of vibration (destructive frequencies tend to be less than 60 cycles/sec).

- Use pulsation dampeners where applicable.

- Provide engineered anchors and braces.

- Account for the potential for two-phase flow conditions by providing extra bracing.

- Use pipe loops to control movement and vibration at equipment connections. Avoid the use of bellows where hazardous materials are involved.

- Allow for thermal expansion by using sliding supports.

- Do not support a valve body and use it to support the attached piping but support the attached piping separately.

- Do not allow a vessel or pump fitting to support attached piping but support the attached piping separately.

- Consider the destructive force of "water-hammer" or "hammer blow" when installing automatic valves. Valves should not be allowed to close more rapidlv than the system can tolerate.

- During installation or repair, do not force piping ends into alignment. This creates extra stress not planned for in the original piping design.

- Use a heavier grade of flange than required by typical practice.

A discussion of the applicability and design of each valve type for use where hazardous materials are involved is presented below.

For reasons discussed previously, it may be preferable to avoid gate valves when using hazardous materials.

Although globe valves have several drawbacks, they are usually the only alternative when automatic flow control is required. When globe valves are used, they should be designed with built-in precautions to prevent misalignment of the disk with the seat. Such precautions could include guides above and below the disk or using a spherical seat. Large globe valves must be installed with the stems vertical.

Valves should be installed with the high-pressure side connected to the top of the disk. This would result in the valve closing if the disk were to separate from the stem.

Plug valves and ball valves probably provide the most reliable form of off/on flow control. However, care must be taken to select a valve with the appropriate overpressure protection where materials with high coefficients of expansion could be trapped and heated or frozen in the valve when it is closed. To ensure adequate sealing, ball valves should be of the fixed ball variety with spring-loaded seats.

Diaphram valves are well-suited for applications where a high level of solids are present in the process fluid. If solids are not a concern, it may be advisable to avoid using diaphragm valves. If the diaphragm fails, then the valve will leak with little or no constriction. These valves are generally limited to low pressure applications and probably should not be used anywhere near their rated maximum pressure. If they are used they should be equipped with packing around the stem.

If there is any potential for corrosion, erosion or fouling, and if the system operates at anything other than moderate pressure, then butterfly valves should be avoided.

Whenever possible, hoses should not be used where hazardous materials are involved, although in some operations it may be impossible to eliminate them. Each hose should be designed to withstand the conditions to which it will be subjected. They should be joined to end connections that can be securely fastened to form joints with other piping. Where more than one type of hose is in use, each variety of hose should use a different type of end connector. The corresponding connectors should only be installed at the process equipment locations where each hose may be used. This will help prevent the use of hoses in applications for which they were not intended.

The above discussion has focused on the individual elements in a piping system. The following discussion lists some design considerations for overall piping systems handling hazardous materials.

- Avoid dead ends or unnecessary and rarely used piping branches. Minimizing piping will reduce the potential for operating errors. Rarely used piping tends to be neglected. Process materials can become trapped in dead ends and result in corrosion, plugging, or unwanted mixing with future incompatible process material.

- Take precautions against liquid holdup. All pipe runs should be pitched to allow liquid to drain. Drains should be at the lowest point in the system. Often this is not the case when piping is installed or when future changes are made. Provisions should be made to prevent a liquid-full condition in a blocked section of line. A liquid-full condition can result in a pipe rupture if the liquid expands as it warms or cools to ambient temperatures.

- Minimize locations in main arteries outside high-integrity block valves. This decreases the likelihood of a main artery leak where rapid isolation could be more difficult.

- Bottom drain lines on vessels handling large volumes of hazardous materials should be limited in diameter. This will limit the rate of material release in the event of a failure in drain line valves. A flow limiter valve which automatically closes if flowrate exceeds a prescribed rate can also be used. Drain lines should always be equipped with two valves in series. A remotely operated emergency isolation valve may be appropriate.

- The line and valve sizes into and out of a vessel should be of the same capacity. If the inlet line has a higher capacity than the outlet, then an overflow is inevitable once control is lost.

- Piping systems should never be designed so that the failure of a single valve will result in a significant accidental release.

Control Effectiveness--

The control effectiveness of various piping design considerations is measured in terms of the reliability of piping system components. Some reliability data are summarized in Table 3-8. The overall reliability of multi-component control measures depends on the reliability of the individual components and on the specific system design or procedure.

Costs--

The costs for each control measure applicable to piping are summarized in Table 3-9, which lists piping hazards, corresponding control measures, and both typical capital and total annual costs associated with each control measure. Table 3-10 presents the design bases for these costs.

Case Examples (1)--

Dead-ends in pipes can be the source of pipe failure when water collects in the dead-end and freezes, breaking the pipe, or when corrosive matter dissolves in the water and corrodes the line. In one case, water and impurities collected in and corroded a dead-end branch of a 12-inch diameter natural gas pipeline operating at a gauge pressure of 550 psi. When the dead-end failed, the escaping gas ignited immediately, killing three men who were looking for a leak.

TABLE 3-8. TYPICAL FAILURE RATES FOR PIPING COMPONENTS

Component	Failure Rate (Failures/Year)
Pipe wall, under 3 inches diameter rupture	8.8×10^{-6}
over 3 inch diameter, rupture	8.8×10^{-7}
Flanged joint, leak or rupture	0.0026
Gasket leak	0.026
Welded joint, leak	2.63×10^{-5}
Valve casing	N/A
Valve stem seal	N/A
Manual valve	
- failure to operate	0.365
- failure to remain open (plug)	0.0365
- leak or rupture	8.8×10^{-5}
Solenoid valve - failure to operate	0.365
Automated valves	
- failure to operate	0.1095
- failure to remain open (plug)	0.0365
- leak or rupture	3.65×10^{-6}
Check valves	
- failure to open	0.0026
- reverse flow leak	1.10×10^{-4}
- rupture	8.8×10^{-5}

Source: References 23, 24 and 28.

TABLE 3-9. EXAMPLES OF PIPING HAZARDS, CONTROL TECHNOLOGIES, AND COSTS

Basis: Costs represent incremental costs over the baseline system presented in Table 3-10.

Hazard	Control Technology	(1986 Dollars)	
		Capital Cost ($)	Total Annual Cost ($/Yr)
General Failure	Corrosion resistant materials.	16,000	2,800
	Higher pressure rating.	2,500	430
	Greater corrosion/erosion allowance.	23,000	4,000
	Monitoring/extra supports.	630	1,000
	Vibration control.	630	55
	Thermal expansion allowance.	750	65
	Heat tracing per 100 ft. of line for freeze protection.	1,000	200
	Fire protection.	200	30
	Increased inspection frequency.	--	800
	Additional piping supports.	630	15
	Avoidance of long unsupported piping runs.	--	--
	Pressure/temperature cycling control.	9,500	1,400
	Valve selection.	--	--
	Control of "hammer blow." (Valve closure rate control)	500	90
	Protection from external physical damage.	60	5
Flanged Joint Failure	Correct flange/gasket combination for intended service.	--	320
	Full diameter, correctly torqued, and full circle bolting.	--	320
	Installation/maintenance supervision.	--	320
	Leak monitoring.	--	1,000
Welded Joint Failure	Correct weld type and materials.	--	320
	Correct weld procedure.	--	320
Pipe Wall Rupture	Double-walled pipe.	7,500	1,300
	Wall thickness testing.	--	1,200
Valve Failure	Installation/maintenance supervision.	--	320
	Correctly sized and torqued body bolding.	--	320

Source: Adapted from References 25, 26 and 27.

TABLE 3-10. DESIGN BASES FOR EXAMPLE PIPING CONTROLS

Piping baseline - 100 ft. of 4 inch, Schedule 40, carbon steel piping with average number of fittings.

Increased corrosion resistance - Same as piping baseline except 316 stainless steel.

Higher pressure rating - Substitute Schedule 80 for Schedule 40.

Greater corrosion/erosion allowance - Substitute Schedule 80, 316 stainless steel for Schedule 40, carbon steel.

Vibration control - Assume an increase in piping supports from one per 14 ft. to one every 7 ft. for 100 ft. of pipeline.

Thermal expansion allowance - Assume addition of an extra loop of 10 ft. of piping to the baseline.

Heat tracing - Assume electrical wrap heat tracing added per 100 ft. of baseline piping.

Fire protection - Assume fireproofing added to baseline piping.

Increased inspection frequency - Assume an increase of 40 hours per year at an hourly total labor cost of $20/hour.

Pressure/temperature cycling control - Assume the installation of a better control loop somewhere in the process unit of which the piping is a part.

Valve selection and control of "hammer blow" - Assume substitution of different valve type.

Protection from external physical damage - Assume 10 ft. of curbing placed around pipe bridge supports.

Correct flange/gasket combination - Assume increased supervisory labor at 8 hours per year and $40 per hour.

Full diameter, correctly torqued bolts, and full circle bolting. Assume increased supervisory labor at 8 hours per year and $40 per hour.

Leak monitoring - Assume monitoring costs as primarily labor at an extra 40 hours per year at $25 per hour.

Correct weld type, material, and procedure - Assume increased supervisory labor at 8 hours per year and $40 per hour.

(Continued)

TABLE 3-10 (Continued)

Double walled pipe - Same basic specification as baseline piping except with double wall allowing for space between inner and outer wall.

Wall thickness testing - Assume inspection labor requirement at 40 hours per year and $30 per hour.

Installation/maintenance supervision - Assume increased supervisory labor at 8 hours per year and $40 per hour.

Correctly sized and torqued body bolting - Assume increased supervisory labor at 8 hours per year and $40 per hour.

In another incident, at a pumping station on a liquid propane pipeline a sudden increase in throughput indicated a major line break. The pipeline failure occurred on high ground and the gas flowed down a sparsely inhabited valley, which was evacuated. The cloud ignited in a sudden flash, creating an overpressure and a fire storm which rolled up the hillside to a highway. The pipeline pressure was believed to have been about 942 psig, and the amount of liquid propane estimated to have escaped in the first 24 minutes was 750 barrels.

3.3.5 Process Machinery

Process machinery is process equipment that contains moving parts and is used to physically treat, handle, or modify process streams. Examples include pumps, compressors, agitators and refrigeration units. The discussion in this section focuses on features common to most types of process machinery and highlights some design considerations for pumps and compressors. Process machinery failures may contribute to accidental releases by directly releasing a toxic chemical contained therein, or by causing a process upset that indirectly leads to a release elsewhere in the process system.

Direct releases from process machinery may occur at the following locations:

- Rotating shaft seals;
- Machinery casing; and
- Machinery attachments.

Causes of releases at these locations are discussed below. Erosion and corrosion are not discussed in any detail since these conditions have been discussed in the previous sections of this manual.

Rotating Shaft Seals--

Process machinery comprises both rotating and reciprocating equipment. A seal is required wherever a rotating or reciprocating device contacts the process fluid. Seals include ring seals on pistons in reciprocating compressors and rotating shaft seals. Rotating shaft seals are far more common in the process plant, and only these are discussed further. Two methods used to make this type of seal are a "packing" or "stuffing" box, or a mechanical seal.

The seal is made in a stuffing box by wrapping the shaft in a woven material and enclosing the wrapped section in a box to hold the packing in place. The advantage of a stuffing box is that the packing is inexpensive and may be easily replaced. The disadvantage is that a packing box does not form a complete seal. At high speeds a packing box must leak to allow for lubrication between the shaft and the packing. These devices are not usually appropriate for use with toxic materials.

A mechanical seal is a prefabricated assembly that forms a running seal between flat, precision-finished surfaces. A mechanical seal can leak because of wear, incorrect installation, erosion, or system overpressure. A mechanical seal depends on a precise contact of the two sealing surfaces. A scored, corroded or in any way deformed shaft can result in a seal failure. The presence of solids in the pumping fluid can destroy the integrity of a seal, which is more of a problem when pumping gases with solids than liquids with solids.

A seal that is not properly installed can fail; all components of the seal must be precisely aligned. Most older pumps were designed for stuffing and the stuffing box may not be big enough to accommodate the seal. A seal installed with too small a clearance could fail because of overheating (29). Even a properly installed seal will fail eventually as a result of wear between the sealing surfaces.

Machinery Casings--

A release from a machinery casing may be caused by stress, corrosion, or erosion.

There are both internal and external sources of stress on a machinery casing. An internal source of stress would be overpressure of the process fluid. External sources of stress include vibration, unsupported weight of attached piping, or improperly torqued, especially overtorqued, bolting that holds casing parts together. These stresses can cause deformation or cracking of the casing.

Corrosion and erosion may be caused by many of the factors listed in previous sections. A pump or compressor casing is particularly susceptible to corrosion and erosion because of the high velocity and turbulence of the fluid. The presence of solids can result in significant wear on the casing and the internals of the pump or compressor. The combined action of corrosion and erosion can significantly reduce the life of a casing.

The casing on positive displacement pumps and compressors can fail because of flow blockage at the discharge (deadheading) or flow blockage at the inlet (resulting in cavitation). Deadheading will result in an overpressure, and if not relieved, can cause a ruptured casing.

The casing on centrifugal pumps and compressors can also fail because of flow blockage at the discharge. The liquid or gas trapped in the pump or compressor will be heated if the device is left running after the discharge has been blocked. This heating can cause thermal decomposition of the process fluid or thermal expansion if both the inlet and discharge are blocked. Both may result in an overpressure and failure of the casing.

Cavitation can result in vibration, erosion, and overheating resulting from the formation and collapse of vapor cavities in the liquid at the metal-liquid interface. Impellers are most frequently affected by cavitation;

however, damage to an impeller can cause excess vibration, which can result in a failure of the casing.

The forces that can cause the failure of a machine casing can cause the failure of a machinery attachment. Process machinery is often the source of most of the vibrations in a process. This vibration is often amplified as it is transmitted to piping and supports and can be very destructive.

Some machinery attachments may fail because of neglect, abuse or improper design. A pump case drain line will usually require a long nipple before mounting the drain valve. An excessive force (operator standing on the drain) may break the line. Sometimes the machine attachments provided by the manufacturer will be improperly designed for the specific application for which the machine is being purchased. A compressor, pressure relief device that comes attached to a compressor should be carefully evaluated. Unless specifically communicated, the assumptions under which the manufacturer sized the pressure relief may not be compatible with the requirements of the actual process.

Process Machinery Failure Prevention Controls--

Stuffing or packing boxes may not be appropriate for toxic chemicals because these devices do not form a tight seal and small amounts of liquid, vapors, or gases are released during normal operation. Enclosing the pump in a ventilated enclosure connected to a control device (such as a scrubber) may be possible but may not be an acceptable alternative in many situations.

A properly installed single mechanical seal will typically operate for about a year without any detectable release of material (29). A seal can fail prematurely for any number of reasons, and for toxic chemicals, any failure may be considered unacceptable. A number of levels of control can be achieved by altering the seal design. Seal performance might be improved by using a larger seal, which will result in a longer wear life. A cartridge seal comes preassembled and may be used to avoid some of the potential installation errors of standard seals. A bellows seal is a mechanical seal designed in a way that reduces the potential for seal plugging over conventional spring designs.

The most effective method for controlling accidental releases from mechanical seals is to use two seals. Further protection may be added by using a sealing fluid between the two seals. Where hazardous materials are involved, the sealing fluid must be compatible with the process fluid and it may be necessary to monitor the sealing fluid for the presence of the process fluid.

In addition to seals, there are many other specific design considerations for pumps and compressors which are discussed in the remainder of this subsection.

Some kinds of pumps do not require mechanical seals and are less susceptible to failures that might directly result in an accidental release. A canned-motor pump is designed so that the motor rotor and pump casings are interconnected; the motor bearings run in the process liquid and all seals are eliminated. Eliminating the seal reduces the potential for an accidental release from these pumps. Because the motor is exposed to the process fluid, their use is restricted to nonabrasive and relatively noncorrosive fluids. Repairing these pumps may require employee exposure to the pumping fluid and thus they may not be suitable where toxic materials are involved.

A diaphragm pump is another type that does not employ a mechanical seal. This pump uses the reciprocating action of a flexible diaphragm to move the process fluid. A diaphragm pump can be mechanically or pneumatically driven. The advantage of this type of pump is that only the diaphragm contacts the liquid. The disadvantage is that eventually the diaphragm will break as a result of wear or overpressure. If these pumps are used for toxic materials, precautions must be taken to avoid an accidental release when a diaphragm fails, which can be accomplished by totally enclosing the pump in a ventilated enclosure; the vent gas going to a control device. An alternative is to connect just the nonprocess side of the diaphragm to a controlled vent. The pumping system design must account for the potential of explosive mixture formation when a diaphragm ruptures on a pneumatically actuated pump.

A final variety of sealless pump is one where the impeller and motor are linked magnetically. The impeller is totally enclosed and leakage is possible only by failure of the impeller casing. These pumps are generally used only for very small, low pressure pumping operations.

Overpressure protection is important for pumps and compressors. The potential for deadheading a positive displacement pump can be reduced by using a pump return loop which connects the discharge directly to the intake and allows liquid to continue to circulate when flow is stopped downstream of the pump loop. The loop should be sized to accommodate the minimum flowrate required by the pump. The danger of using a pump return loop is that the loop creates a route for potential backflow when the system is shut-off. A system's design must provide sufficient backflow protection in such a situation.

Where hazardous materials are involved, pressure relief from pumps and compressors must be piped to a total containment system. The backpressure created by the containment system must be accounted for in sizing the pressure relief device.

It may often be appropriate to install remotely controlled emergency isolation valves at the intake and discharge of a pump or compressor that is handling a hazardous material. This combined with a remote pump shutoff switch allows flow to be stopped in the event of an accidental release from the pump or compressor. Where two pumps are parallel, an alternative or addition to the above recommendations would be to add the ability to remotely switch from one pump to the other.

Care must be taken whenever encasing a pump or compressor in a vented enclosure. While providing some accidental release protection, such enclosures can be a trap for flammable mixtures. To avoid this, vented enclosures should be purged with an inert gas, or with sufficient quantities of air to keep the level of flammable vapors below the flammable limit. In either case, the contents should be monitored for the presence of flammable mixtures.

A number of pump parameters can be continuously monitored to help detect potential failures before they occur. The following pump or compressor parameters can be monitored: overspeed, low oil pressure, high jacket-water temperature, high gas discharge, high oil temperature, high level on knockout drums, overload relays, vibration monitors, bearing load cells, and temperature indicators imbedded in bearings. Incipient failure detection is discussed in more detail in Section 4 under maintenance and modification practices.

Control Effectiveness--

The control effectiveness of various process machinery design considerations depends on the reliability of system components. Some reliability data are summarized in Table 3-11. The overall reliability of multicomponent control measures involving machinery depends on the reliability of the individual components and on the specific system design or procedure.

Costs--

Table 3-12 summarizes costs for some example control measures applicable to process machinery. This table lists process machinery hazards, corresponding control measures, and both typical capital and total annual costs associated with each control measure. Design bases for the costs are presented in Table 3-13.

Case Examples (31)--

In a polyethylene plant, fatigue failure of a vent connection on a compressor suction line allowed ethylene to escape. A gas cloud formed and later ignited. Highly directional pressure waves caused widespread damage. Six people were killed and thirteen injured.

TABLE 3-11. TYPICAL FAILURE RATES FOR PROCESS MACHINERY COMPONENTS

Component	Failure Rate (Failures/Year)
Pumps	
- Failure to start	0.365
- Failure to run	0.011
- Shaft seal, major leak	5×10^{-3}
Compressors	N/A

Source: Adapted from References 23 and 24.

TABLE 3-12. EXAMPLE PROCESS MACHINERY HAZARDS, CONTROL TECHNOLOGIES, AND COSTS

Basis: Costs represent incremental costs over the baseline system presented in Table 3-13.

Hazard	Control Technology	(1986 Dollars) Capital Cost ($)	(1986 Dollars) Total Annual Cost ($/Yr)
General Failure	Corrosion resistant materials.	2,500	430
	Higher pressure rating.	3,000	520
	Greater corrosion/erosion allowance.	3,000	520
	Vibration monitoring and control.	--	800
	Freeze protection.	250	50
	Increased inspection frequency.	--	800
	Installation/maintenance supervision.	--	320
	Full bolting with correctly torqued bolts.	--	320
	Pressure/temperature cycling control.	9,500	1,400
	Control of hammer blow.	500	90
	Adequate overpressure protection.	--[a]	--
	Protection from external physical damage.	120	10
Shaft Seal Failure	Proper seal type for service.	1,000	90
	Proper seal materials and construction.	--[b]	320
	Adequate seal flushing, lubrication, and cooling.	--	320
	Adequate overpressure protection.	--	--
	Vibration monitoring and control.	--	800
	Increased inspection frequency.	--	800
Bearing Failure	Specialized acoustic monitoring.	--	800
	Preventive maintenance.	--	160

Source: Adapted from references 25, 26 and 27.

[a] Costs depend on specific systems used which are not directly related to the process machinery itself.

[b] Proper seal material depends on specific service.

TABLE 3-13. DESIGN BASES FOR PROCESS MACHINERY CONTROLS

Baseline equipment - Centrifugal pump, carbon steel, 250 gpm, 150 psig rating, stuffing box seal.

Corrosion resistant materials - Same as equipment baseline except 316 stainless steel.

Higher pressure rating, greater corrosion/erosion allowance - Same as equipment baseline except heavier casing.

Vibration monitoring - Assume equivalent cost of 40 hours additional operating labor per year at $20 per hour.

Vibration control - Assume heavier foundations and supports.

Freeze protection - Assume 25 ft. of heat tracing.

Increased inspection frequency - Assume an increase of 40 hours per year at an hourly total labor cost of $20/hour.

Full bolting with correctly torqued bolts - Assume increased supervisory labor at 8 hours per year and $40 per hour.

Pressure/temperature cycling control - Assume the installation of a better control loop somewhere in the process unit of which the pump is a part.

Control of "hammer blow" - Assume substitution of different type of valve or valve closure mechanism in liner connected to pump for a 4-inch pipeline.

Adequate overpressure protection - No general estimate possible. Costs depend on specific systems used which are not directly related to the process machinery itself.

Protection from external physical damage - Assume curbing around pump area for perimeter of 20 ft.

Proper seal for type of service - Double mechanical seal substituted for stuffing box seal on baseline centrifugal pump.

Proper seal materials of construction - Assume increased supervisory labor at 8 hours per year and $40 per hour. Actual seal materials depend on specific service.

Adequate seal flushing, lubrication, and cooling - Assume increased supervisory labor at 8 hours per year and $40 per hour. Actual seal flush system depend on specific service.

Specialized acoustic monitoring for bearings - Assume equivalent cost of 40 hours additional operating labor per year at $20 per hour.

Preventive maintenance - Assume bearing replacement once a year.

Failure of a pump in a butadiene processing unit spilled an estimated 27,000 lb of butadiene that resulted in a vapor cloud release which drifted 600 feet before igniting 10 minutes later. One person was killed, six were injured, and the plant suffered major damage.

3.3.6 Instrumentation and Control System Hardware

Mechanical failure of the components of a facility's instrumentation and control system can cause a loss of process control which could result in an accidental release. The relationship between process control and the potential for an accidental release was discussed in Section 2 of this report. This section focuses on potential mechanical failures for the various components of a control system. It does not address the problems that may result from poor control system logic, which was also addressed in Section 2.

Instrumentation equipment may fail as a result of the following conditions:

- Corrosion,
- Erosion,
- Mechanical deterioration, and
- Fouling.

The relative importance of these potential causes of instrumentation failure depend on the kind of instrumentation involved. For example, corrosion may be a significant consideration for temperature measurement devices, while fouling is a well-known problem with pH control systems. The various listed conditions are discussed below.

Corrosion--

Both internal and external corrosion can damage instrumentation and control system components. Any components that contact a process stream can be subject to internal corrosion. The nature and concentration of the corrosive agents in the stream and the materials of construction of the component determine the potential for internal corrosion. Corrosion damaging to system operation is most often encountered in such control components as control-valves, orifice plates, analyzers, chambers of certain level instruments, gage glasses, probes, or any other device in direct contact with a corrosive process stream. Internal corrosion can cause moving parts to seize, and membranes or sensing elements can be destroyed. Such failures can make sensing and other functions impossible and cause a loss of control. Corrosion can also cause leaks through instrument connections and housings.

External corrosion can be caused by moisture, salt air, fungi or corrosive vapors in the atmosphere. The American Petroleum Institute states that "in hot, humid climates, these factors are the major causes of instrument component failure" (29). Electrical components are susceptible to failure by external corrosion. The formation of oxides, and the growth of fungus are examples of external corrosion that can alter electrical properties and prevent some portion of a system's electronics from functioning properly. In more severe cases, external corrosion can destroy the physical integrity of casings, conduit, or other structural portions of a control system. Such deterioration could result in a failure of the control system by exposing the internal portions of the system to the same corrosion that destroyed the external portions.

Erosion--

The portions of a control system exposed to flowing process streams are susceptible to erosion, especially streams containing significant amounts of suspended solids. The high pressure drop and rapid fluid motion through an orifice plate make it susceptible to erosion. Erosion of the orifice would result in an altered pressure-to-velocity relationship and hence in failure of the device. Any sensor the protrudes into a flowing stream, such as a thermowell, can be subject to failure by erosion. Failure occurs when erosion has physically destroyed the sensing element. The operation of a control valve and its ability to accurately regulate flow can be impaired by erosion.

Mechanical Deterioration--

Several kinds of mechanical deterioration can affect a control system. Examples of cases of mechanical deterioration include: fatigue failure and wear, mechanical abuse, exceeding instrument limits, and overheating or freezing.

Any instrument with moving parts is subject to fatigue failure and wear. Instruments that oscillate over a narrow portion of the operating range are most susceptible to wear. This type of wear can result in cracked, bent, or broken moving parts. Seals and bearings will eventually wear out. Fatigue failure can also be caused by external vibration or by the weight of unsupported attached equipment. Such forces can result in cracked, bent, or broken casings or internals.

Mechanical abuse is damage that results from careless maintenance or operation. Examples of mechanical abuse damage are broken glass, damaged housings, and bent valve stems. Damage can occur when personnel use instruments attached to equipment as steps to climb on equipment. Control-valve stems can be distorted from excessive torque if valve wrenches on the handwheel are used to free binding valves. Equipment may be damaged by collision with moving maintenance equipment.

Each instrument has a specific acceptable operating range and exceeding this range may result in permanent damage to the instrument. Acceptable operating limits are usually placed on the variable being monitored by the instrument, on some of the chemical and physical properties of the process stream and on the electrical power supply. For example, a stainless steel bourdon tube pressure gauge may be equipped to monitor pressures from 0 to 500 psi. Such a gauge may fail if subjected to greater than 750 psi pressures, to temperatures over 500°F, or to acidic process streams, depending on the materials of construction.

Exposure of instrumentation to external sources of heat or to freezing temperatures can cause instrument malfunctions. External sources of heat could include fires, adjacent hot equipment or even direct sunlight in some cases. Heat can alter or impair the performance of or damage the electronic components of the system, such as heat-sensitive sensing devices. Extreme heat (such as fire) can cause total destruction of the instrument. Low ambient temperatures can also have adverse effects. For example, freezing may impair free movement of parts.

Fouling--

Portions of a control system exposed to process streams are subject to fouling from direct deposition of contaminants or by or reaction by products in the streams. Fouling may block a sensing element from exposure to the stream it is intended to monitor, thus preventing the system from controlling the condition of the stream.

Design Considerations--

In designing control system hardware, proper initial instrument selection may be the most effective method for reducing the potential for subsequent failures. For almost every process variable at least two kinds of sensing devices are available, each kind functioning on a different principle. Different ranges are usually available for each device. For each range several different materials of construction are likely to be available, which means that for every specific application there are opportunities to select combinations of specifications suitable for any particular service.

Selecting an appropriate sensor may not be a simple matter. The more information available about the operating conditions, the easier the selection will be. Since vendors will be quick to point out the advantages of their device, it will often be up to the designer to explore all of the alternatives available and use engineering judgement to make a selection. Guidance is available from the technical literature that describe how various sensing devices work and that aids in selection (29). From a practical perspective, it is not always possible to pick a sensing device clearly superior to the alternatives. For critical applications it may be necessary to install redundant sensors that operate on different principles. Such redundancy should be considered wherever the failure of a sensor would significantly contribute to the potential for an accidental release.

Devices that protect a sensing element from severe process conditions are also available. Such special protection should be considered whenever the process involves a hazardous material. These devices are designed to lengthen the life and therefore improve the reliability of the instrumentation. Many of these protective devices can reduce the accuracy or increase the response time of the sensor they are protecting, which must be taken into consideration when incorporating such a device into a control system. Examples of some protective devices are discussed below.

Pressure sensors are almost always protected from direct contact with the process stream by various types of diaphragms. They may also be protected from damage by sudden shock pressure or rapidly fluctuating pressure by pulsation dampeners. Temperature sensors are often protected from the process stream by a thermowell. Other probes can be protected from physical damage by perforated casings. Where solids are present, a sensor may be installed in a filtered slip stream. Where fouling is likely to occur, automatic or manual cleaning devices are available to periodically remove solid buildup on a sensing surface.

Extra support, shielding and vibration suppression equipment may be in order for various components in a control system. Where possible, sensitive electronic portions of the system should be protected. Often, the sensor, transducers and control valves are the only parts of the control system that need to be out in the process itself. The rest of the system can often be placed in the protected environment of the control room.

Operator training will help prevent failures caused by abuse. Regular inspection will help reduce the potential for an accidental release by correcting instrument problems before they occur. The operation of most control equipment can be tested on line without shutting down the process. Control systems that oscillate around the set point should be returned before such oscillation results in a failure. Control systems should be protected from damage during shutdown or repair. Sensors may need to be isolated before pressure or leak testing is performed, or before equipment is cleaned. Control systems may also need protection during sandblasting or painting.

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SECTION 4
PROCEDURES AND PRACTICES

A well-designed and operated process, quality hardware and mechanical equipment, and protective devices all increase plant safety; however, they must be supported by the safety policies of management and by clear specifications on their operation and maintenance. This section describes how management policy and training, operation, and maintenance procedures relate to the prevention of accidental chemical releases. Within the chemical industry, these procedures and practices vary widely because of differences in the size and nature of the processes and because any determination of their adequacy is inherently subjective. For this reason, the following subsections focus primarily on fundamental principles and do not attempt to define specific policies and procedures.

4.1 MANAGEMENT POLICY

Management is a key factor in controlling industrial hazards and preventing accidental releases. Management establishes the broad policies and procedures that influence the implementation and execution of specific hazard control measures. It is important that these management policies and procedures be designed to match the level of risk in the facilities where they will be used. Most organizations have a formal safety policy. Many make policy statements to the effect that safety must rank equally with other company functions, such as production and sales. The effectiveness of any safety program, however, is determined by a company's commitment to it, as demonstrated throughout the management structure. Specific goals must be derived from the safety policy and supported by all levels of management. Safety and loss prevention should be an explicit management objective. Ideally, management should establish the specific safety performance measures, provide incentives for attaining safety goals, and commit company resources to safety and hazard control. The advantages of an explicit policy are that it sets the standard by which existing programs can be judged, and it gives evidence that safety is viewed as a significant factor in company operations.

In the context of accident prevention, management is responsible for (1, 2, 3):

- Ensuring worker competency;
- Developing and enforcing standard operating procedures;
- Adequate documentation of policy and procedures;
- Communicating and promoting feedback regarding safety issues;
- Identification, assessment, and control of hazards; and
- Regular plant audits and provisions for independent checks.

Because human error is a common cause of accidental chemical releases, personnel selection and maintenance of a qualified, experienced workforce is a significant part of release prevention. Managers are responsible for ensuring that personnel selection procedures adequately assess worker competency and match worker skills to job responsibilities. One author identified such abilities as signal detection, signal filtering, probability estimation, manual control, and fault diagnosis as important process operator skills (1). In addition, however, personal characteristics, practical training and recent relevant experience should be considered in the selection process. The ideal process operator should be responsible, conscientious, reliable, and trustworthy (1). Temperament is important since it affects a previous response to monotony and stress. Motivation and communication skills are other personality traits that could be assessed during personnel selection. Particular care should be taken when selecting operators for facilities handling hazardous materials. The qualifications and capabilities of personnel in high hazard facilities should be higher than for those in other process facilities.

Many accidental release incidents and/or major industrial disasters have been caused in part by a failure to properly assign responsibilities (1, 2). It is just as important to avoid a situation where positions critical to safety maintenance are left unoccupied; accidents have been attributed to situations in which key safety responsibilities were vacated and left unassigned. An effective management policy sees that the responsibilities of such positions are carried out even in the event of resignations and absences.

The responsibility for safety issues such as release prevention should be shared by all management and workforce staff. The staff must be supported by procedures for staff training in operating and maintenance practices, handling upset and emergency conditions, using safety equipment, and performing facility audits. Establishing standard practices for these activities is necessary to ensure uniformity, avoid confusion, and make enforcement possible. The enforcement of standard procedures is one of management's most fundamental responsibilities in the area of facility safety and accident prevention.

Management is also responsible for ensuring that an adequate description of safety policy and standard procedures is available. In the chemical industry, a great deal of documentation is produced covering areas from design and layout, operation, maintenance, and inspection, hazard identification and assessment, and emergency planning. So that procedure and policy statements will not be overly cumbersome and monotonous, these documents should:

- Be easy to use;

- Be complete;
- Establish the importance and benefits of the procedures;
- Be clear and concise.

The document should be written to a specific audience. In other words, the users of the policy and procedures document must feel it addresses them. These documents should explain not only how release prevention activities are conducted, but also why it is important that they be conducted in the specified manner, so that the benefits of proper safety practices will be clear. Finally, attention to readability and style should be an important priority in document preparation, since if personnel find the documents cumbersome and wordy, they won't read them and they will not be easy to use as references.

Publicizing safety material is not enough, since personnel often think these bulletins are dull (1, 2, 3). Encouraging communication, promoting feedback, and emphasizing facility safety as a matter of professionalism are examples of ways of countering "safety boredom." Active communication stressing the priority of accident prevention should come from all levels of management, so that personnel will feel that discussion of the effectiveness of current safety standards and ideas for improvement is an important part of their job. When management demonstrates a willingness to respond to initiatives from below and participates directly with workers in improving safety, worker morale increases, increasing the degree to which standard procedures are followed. Assigning safety and loss prevention responsibility to competent people and giving them specific, meaningful objectives and adequate resources also encourages a professional attitude about the importance of safety.

Hazard identification, assessment, and control is another area that should be addressed by management to minimize the potential for accidental chemical release incidents. In the past, these activities have been handled relatively informally; however, many companies now use a more systematic approach (3). In most instances, safety hazards are identified by the experienced staff. Safety review committees that evaluate processes by a "what if" approach are an example of using staff experience to identify hazards. The objective of hazard assessment techniques is to gather information on how frequently accidents could occur, how severe the consequences could be, and what changes could be made in processes, equipment and procedures to reduce the accidents and their consequences. Management must have a mechanism for obtaining this type of information so that they can rank potential problems and decide how to allocate hazard control resources. Various analytical techniques, both qualitative and quantitative, are available for performing hazard assessments (1, 2, 3). Managers are responsible for hazard control decisions during the design, construction, startup, operation, maintenance, and shutdown of chemical process facilities. Hazard control has typically been aimed at minimizing the potential for incidents such as fires and explosions; however, prevention of accidental chemical releases should also be a fundamental consideration.

A facility safety audit is a frequently used activity associated with hazard identification, assessment, and control. A total facility safety audit involves a thorough evaluation of a facility's design, layout, equipment and procedures, and is aimed specifically at identifying and correcting potentially unsafe conditions. Audits are often conducted during facility startup and repeated a year after startup. Thereafter, the frequency of safety audits varies, typically ranging from every two to five years. Specific objectives of these audits include alerting operating personnel to process hazards, determining whether or not safety procedures need to be changed, screening for equipment or process changes that may have introduced new hazards, assessing the feasibility of applying new hazard control measures, identifying additional hazards, and reviewing inspection and maintenance programs (4).

In-house safety audits are generally the responsibility of senior management and are conducted by teams selected by these managers. One review of audit procedures recommended that audit committees include the plant manager, a safety department representative, a project or design engineer, a maintenance engineer, a process engineer, and an instrumentation/control engineer (5). Another system is the independent safety audit, which is conducted by qualified consultants or insurers. One of the primary advantages of hiring independent entities to perform safety audits is that in addition to evaluating facility safety, they check management organization, policies, and attitudes.

4.2 OPERATOR TRAINING

The performance of operating personnel is a significant factor in preventing accidental chemical releases. Many case studies documenting industrial incidents note the contribution of human error to accidental releases (1,2). Causes of release incidents include improper routine operating procedures, insufficient knowledge of process variables and equipment, insufficient knowledge of emergency or upset procedures, failure to recognize critical situations, and, in some cases, a direct physical mistake (e.g., turning the wrong valve). A comprehensive operator training program can decrease the potential for accidents resulting from such causes.

Operator training can include a wide range of activities and a broad spectrum of information. Training, however, is distinguished from education in that it is specific to particular tasks. While general education is important and beneficial, it is not a substitute for specific training. The content of a specific training program depends on the type of industry, the nature of the processes used, the operational skills required, the characteristics of the facility management system, and tradition.

Some general characteristics of quality industrial training programs include:

- Establishment of good working relations between management and personnel;
- Definition of trainer responsibilities and training program goals;
- Use of documentation, classroom instruction, and field training (in some cases supplemented with simulator training);
- Inclusion of procedures for normal startup and shutdown, routine operations, and upsets, emergencies, and accidental releases; and
- Frequent supplemental training and the use of up-to-date training materials.

In many instances, training is carried out jointly by facility managers and by a training staff selected by management. In others, management is solely responsible for maintaining training programs. In either case, responsibilities should be explicitly designated to ensure that the quality and quantity of training provided is adequate and that there is accountability for the training. Training requirements and practices can be expected to differ between small and large companies, partly because of resource needs and availability, and partly because of differences in employee turnover.

The job of the trainer is essentially to ensure that the right type and amount of information is supplied at the right time. To do this the trainer must not only understand the technical content of a job, but also those aspects of the job where operators may have difficulty. It is therefore advantageous for trainers to spend time observing and analyzing the tasks and skills they will be teaching. This is referred to by Lees as prior-task analysis, and is important for finding out which factors affect the learning of skills and how training programs can be organized to best address difficult areas (1).

Factors such as pace, motivation, and feedback are standard considerations in educational and training applications (1). Training programs should be conducted at a pace that allows operators to become thoroughly familiar with the material. Maintaining motivation is essential; interest in the material can be fostered by focusing not only on how tasks are conducted but on why they are performed the way they are (e.g., pointing out the hazards associated with improper procedures can motivate workers to do the job properly and safely). Finally, performance feedback and reinforcement during training is needed to correct poor technique, resolve misunderstandings, reward good technique, and encourage further skill development.

Training programs may use a combination of classroom training, where lectures can and should be supplemented with written material (e.g., specific training documents as well as copies of standard operating procedures), simulator training, and training within the facility itself. In-facility training is particularly effective because it allows the operator to become familiar with the actual process layout and to learn directly how to operate equipment and instrumentation. During facility startup, valuable in-facility training exercises can be conducted in hazardous areas using safe fluids instead of actual process chemicals (2). Digital simulators are extremely useful training devices, particularly for training in high-hazard areas. Using these devices to closely simulate process operation allows training to be conducted without endangering either a process or an inexperienced operator. Although simulators are useful in routine operator training, they are perhaps even more important for upset and emergency training. Simulated emergencies are an effective way to allow operators to witness a variety of situations and make judgements in a non-stressful environment (6).

The objectives of normal operator training are to familiarize operators with the nature of processes, equipment, chemicals, and standard operating procedures. A list of the aspects typically involved in the training of process operators is presented in Table 4-1.

Upset and emergency training typically augments the information presented during routine training. Ideally, emergency training should be integrated with routine operation training (2). This kind of presentation allows operators to become familiar with processes as a whole and illustrates how both process characteristics and operator responses evolve from normal operation to upset and on to emergency conditions. Emergency training includes topics such as:

- Recognition of alarm signals;
- Performance of specific functions (e.g., shutdown switches);
- Use of specific equipment;
- Actions to be taken on instruction to evacuate;
- Fire fighting; and
- Rehearsal of emergency situations.

Safety training includes responses to emergency situations, but is also concerned with preventive measures. Safety courses are typically required of new operators at chemical process facilities, and frequently these courses are later supplemented by more thorough safety training. Aspects specifically addressed in safety training include (1, 3):

- Hazard recognition and communication;
- Actions to be taken in particular situations;

TABLE 4-1. ASPECTS OF TRAINING PROGRAMS FOR ROUTINE PROCESS OPERATIONS

- Process goals, economics, constraints, and priorities
- Process flow diagrams
- Unit operations
- Process reactions, thermal effects
- Control systems
- Process materials quality, yields
- Process effluents and wastes
- Plant equipment and instrumentation
- Equipment identification
- Equipment manipulation
- Operating procedures
- Equipment maintenance and cleaning
- Use of tools
- Permit systems
- Equipment failure, services failure
- Fault administration
    - Alarm monitoring
    - Fault diagnosis
    - Malfunction detection
- Communications, recordkeeping, reporting

Source: Reference 1.

- Available safety equipment and locations;

- When and how to use safety equipment;

- Use and familiarity with documentation such as:
  - plant design and operating manuals,
  - company safety rules and procedures,
  - procedures relevant to fire, explosion, accident, and health hazards,
  - chemical property and handling information; and

- First aid and CPR.

Although emergency and safety programs traditionally focus on incidents such as fires, explosions, and personnel safety, the prevention of accidental chemical releases and release responses should also be addressed. Release incidents are often overlooked because, except for infrequent catastrophes, their impact can be less dramatic than that of fires or explosions. Combined training with responding agencies is also a good practice because it allows personnel from both sides to learn how to adapt their procedures to increase the benefits of a joint emergency response effort.

The frequency of training and the frequency with which training materials are updated (1-5) are also important in maintaining strong training programs. One of the main problems associated with industrial training programs is that the level of training provided during facility startup (or new employee orientation) is often not followed up during the life of the facility (or in the case of the employee, during his career) (2). Additional training programs, such as refresher courses, offer many advantages, particularly when they cover procedures that may not be used very often (e.g., startup, shutdown, upset, emergency). In some instances, experienced operators may become careless or complacent, and additional training reminds them of the importance of following proper procedures. Chemical processes may be modified to the extent that equipment changes require operational changes. Supplemental training ensures that operators are aware of the changes and of the safety considerations that accompany them. Another advantage of training experienced operators is that these workers can often point out the weaknesses and inadequacies in documented procedures and suggest alternate techniques. Differences in turnover in different companies also affect the experience profile of the operating staff and influence the frequency of training.

Maintaining updated training materials and updated process design and operating manuals is the responsibility of managers and training personnel. These materials should be reviewed regularly, especially when plant modifications are made, to ensure that workers have access to up-to-date descriptions and procedures.

Much of the type of training discussed above is also important for management personnel. Safety training gives management the perspective necessary to formulate good policies and procedures, and to make changes that will improve the quality of facility safety programs. Lees suggests that training programs applied to managers include or define (2):

- Overview of technical aspects of safety and loss prevention approach;
- Company systems and procedures;
- Division of labor between safety personnel and managers in with respect to training; and
- Familiarity with documented materials used by workers.

The training programs in effect in industries using, manufacturing, and storing toxic chemicals represent an effort to minimize the potential for accidental release and, therefore, should be considered as important as physical containment. The training fundamentals presented here are only an introduction to some features of the types and content of specific training that can be provided, but they highlight the importance of a good training program in fostering a staff genuinely concerned with safety and aware of how their actions can affect safe operation of the facility.

4.3 MAINTENANCE AND MODIFICATION PRACTICES

Maintenance practices include both general practices that involve overall maintenance policy and procedures, and specific practices for specific maintenance objectives.

4.3.1 General Practices

Proper facility maintenance ensures the functional and structural integrity of chemical processing equipment, ancillary equipment, and services. Modifications are often necessary to allow more effective production, reduce costs, or enhance safety. However, since these activities can be a primary source of accidental release incidents, proper maintenance and modification practices are an important part of accidental release prevention. Use of a formal system of controls is perhaps the most effective way of ensuring that maintenance and modification are conducted safely. In many cases, formal control systems have had a marked effect on the level of failures experienced (2).

Maintenance refers to a wide range of activities, including preventive maintenance, production assistance (e.g., adjustment of settings), servicing (e.g., lubrication and replacement of consumables), running maintenance, scheduled repairs during shutdown, and breakdown maintenance. These activities in turn require specific operations such as emptying, purging, and cleaning vessels, breaking pipelines, tank repair or demolition, welding, hot tapping (attaching a branch to an in-service line), and equipment removal (2).

The potential for accidents during these types of procedures is quite high. Two of the more common maintenance problems have been identified as equipment identification and equipment isolation (2). Accidents frequently result from incorrect identification of the equipment on which work is to be done. This can have disastrous effects, especially if connections associated with high temperature, high pressure, or hazardous material operations are involved. Failure to adequately isolate equipment is another major source of maintenance accidents. To protect process and maintenance personnel, it is essential to have positive isolation of both process materials and moving parts during maintenance activities. Other potential sources of maintenance accidents are improper venting to relieve pressure, insufficient draining, and not cleaning or purging systems before maintenance activities begin.

Permit systems and up-to-date maintenance procedures minimize the potential for accidents during maintenance operations. Permit-to-work systems control maintenance activities by specifying the work to be done, defining individual responsibilities, eliminating or protecting against hazards, and ensuring that appropriate inspection and testing procedures are followed. Such permits generally include specific information such as (2):

- The type of maintenance operations to be conducted;
- Descriptions and identifying codes of the equipment to be worked on;
- Classification of the area in which work will be conducted;
- Documentation of special hazards and control measures;
- Listing of the maintenance equipment to be used; and
- The date and time when maintenance work will be performed.

Maintenance permits originate with the operating staff. In this way, operators and operations supervisors are aware of impending maintenance activities and are instructed to make any required operating changes and properly isolate the equipment to be serviced. Permits may be issued in one or two stages. In one-stage systems, the operations supervisor issues permits to the maintenance supervisor, who is then responsible for his staff. Two-stage systems involves a second permit issued by the maintenance supervisor to his workforce (2).

Permit-to-work systems offer many advantages. They explain the work to be done to both operating and maintenance workers. In terms of equipment identification and hazard identification, they provide a level of detail that significantly reduces the potential for errors that could lead to accidents or releases. They also serve as historical records of maintenance activities. To make sure that these systems give the desired protection, various authors recommend that they be reviewed as part of facility audit procedures (2, 5).

Another form of maintenance control is the maintenance information system. Such a system can generate information on facility incidents, failures, and repairs (2). Ideally, these systems should log the entire maintenance history of equipment, including preventive maintenance, inspection and testing, routine servicing, and breakdown or conditional maintenance. This type of system is also used to track incidents caused by factors such as human error, leaks, and fires, including identification and quantification of failures responsible for hazardous conditions, failures responsible for downtime, and failures responsible for direct repair costs. This information is used to assess current maintenance practices and to develop maintenance procedures and schedules that increase facility safety and reduce operating costs.

Maintenance of the integrity and safe operation of process equipment depends on proper facility modification practices. To avoid confusion with maintenance activities, a modification is defined as an intentional change in process materials, equipment, operating procedures, or operating conditions (2). Industrial facilities frequently undergo modification; these activities sometimes start during the design phase and nearly always take place during commissioning and operation. Modifications may be temporary or may involve permanent changes to equipment or operation.

Accidental releases frequently result from some aspect of facility modification. Accidents happen when equipment integrity and operation are not properly assessed following modification, or when modifications are made without updating corresponding operation and maintenance instructions. In many instances, equipment is changed under the stress of attempting to get a facility operating as soon as possible. In these situations, it is important that careful assessment of the modification results has a priority equal to that of getting the facility on line.

Frequently, hazards created by modifications do not appear in the exact location of the change. Equipment modifications can invalidate the arrangements for system pressure relief and blowdown and can invalidate the function of instrumentation systems. Even relatively minor modification can introduce hazards if proper precautions are not taken (e.g., improperly supported bypass lines) (2).

For effective modification control, there must be established procedures for authorization, work activities, inspection, and assessment, complete documentation of changes, including the updating of manuals, and additional training to familiarize operators with new equipment and procedures (2, 3). Several factors should be considered in reviewing modification plans before authorizing work. According to Lees, these include (2):

- Sufficient number and size of relief valves;

- Appropriate electrical area classification;

- Elimination of effects which could reduce safety standards;

- Use of appropriate engineering standards;

- Proper materials of construction and fabrication standards;

- Existing equipment not stressed beyond design limits;

- Necessary changes in operating conditions; and

- Adequate instruction and training of operation and maintenance teams.

Following authorization, established procedures should be used to ensure that work is conducted according to appropriate codes and standards and that systems are fully inspected before commissioning. In many cases, it is advantageous that the people involved with authorizing modifications be involved with the pre-startup inspection.

Formal procedures and checks on maintenance and modification practices must be established to ensure that such practices enhance rather than adversely affect plant safety. As with other facility practices, procedure development and complete documentation are necessary. However, training, attitude, and the degree to which the procedures are followed also significantly influence facility safety and release prevention.

4.3.2 Equipment Monitoring and Testing

The potential for an accidental release may be reduced by repairing or replacing equipment that appears to be headed for failure. A number of testing methods are available for examining the condition of equipment. Some of the most common types of tests are listed below:

- Metal thickness and integrity testing;
- Vibration testing and monitoring; and
- Relief valve testing.

All of the above testing procedures are nondestructive; they do not damage the material or equipment that they test. Only a few of the most common test methods are discussed here. Additional methods and further detail on the methods mentioned here may be found in references on testing procedures (1,2,3,4).

4.3.3 Metal Thickness and Integrity Testing

Metal thickness and integrity tests are used to determine the thickness of metal in vessels and piping and the presence of general corrosion, cracks, pitting, or other defects. These methods are also used to inspect the integrity of welds. The two most common test methods are radiographic testing and ultrasonic testing.

Radiographic testing uses an X-ray type of photograph of the equipment of interest. A radiation sensitive film is attached to one side of a metal surface. A radiation source (usually gamma rays) is opened up on the other side of the metal surface. The radiation penetrates the metal and exposes the film. The end result is an image of the surface and interior of the metal. If properly taken and interpreted, the presence of defects in the metal as well as the thickness of the metal can be determined. This method is often applied to welds, and small diameter pipes, valves and fittings may be radiographed without opening the line or taking it out of service. For larger diameter equipment, the radiation source must be placed inside the equipment, requiring that it be taken out of service. Proper handling of the radiation source and proper interpretation of the radiographic picture require special training. Most companies hire outside specialists to perform their radiography, although some companies have trained in-house personnel.

The advantages of radiography are that it provides a reliable and detailed picture of the condition of the item of interest, and for small equipment that does not have to be taken off line it is a fairly quick testing method. There are several disadvantages of radiography. Many pieces of equipment must be taken out of service and opened up to allow access for the radiation source. In these situations, more time will probably be required to prepare the equipment for testing than will the actual test. Additionally, operating personnel must be cleared from an area of the process when the radiation source is in use. This could require additional process downtime. The radiation from the testing may also interfere with certain types of instrumentation.

In ultrasonic testing, a probe that generates an ultrasonic pulse is held against the bare metal. The thickness of the metal is determined by the instrument measuring the time required for the ultrasonic signal to travel from the probe to the opposite side of the metal surface and back to the probe. Small pieces of metal of known thickness must be available as a reference for each material to be tested. The pulse and echo from the probe are displayed on a cathode ray screen. Special training is required to be able to properly interpret the output from this test. A signal sent perpendicular to the metal surface is used to measure the wall thickness at that spot. By placing the signal probe at various angles, and moving the probe to various locations on the surface, a trained tester can determine the presence of cracks, pits or other irregularities in metal equipment and welds.

The advantages of ultrasonic testing are that it often requires less preparation than radiography. No radiation is involved so testing areas do not have to be cleared of personnel. Equipment does not have to be opened for an ultrasonic test to be performed. But there are several disadvantages to ultrasonic testing. Test results may not be easy to interpret, and it is difficult to generate a permanent copy of the results for future examination. Most ultrasonic equipment is not explosion proof and flammable materials must be eliminated from the testing area. Since the ultrasonic probe cannot be held directly against high temperature surfaces, an insulated material must be used. The insulation, however, reduces the sensitivity of the probe.

Other test methods are available but less commonly used. These include; magnetic-particle examination, liquid-penetrant examination, eddy-current test method, thermography and electrical-resistance test method. The magnetic-particle and liquid-penetrant examination methods are simple procedures used for detecting the presence of surface cracks. The eddy-current test method is often used to test the integrity of tubing. The electrical-resistance test method, which is used to locate flaws in metal structures, has been used for years by railroads to locate transverse cracks in rails. Additional details of these and other testing methods may be found in the technical literature (1,2).

4.3.4 Direct Corrosion Monitoring

Direct corrosion monitoring is accomplished by visual inspection, using corrosion coupons, or various instrumental methods that measure corrosion products in process streams. The shortcomings of these methods, especially the coupon method, is that special circumstances, such as corrosion in a specific area of equipment caused by localized stress conditions, for example, might not be detected.

4.3.5 Vibration Testing and Monitoring

Vibration testing and monitoring is used to detect incipient equipment failure and to diagnose what part of the equipment is failing. The basic premise of vibration testing and monitoring is that defects in piping, structural supports or machinery are characterized by corresponding abnormal vibrations.

Vibrations are measured using a variety of methods. A common vibration measuring probe is the accelerometer, which measures the motion of the probe relative to a motionless reference mass. A proximity probe is used to measure the motion of one point relative to another.

The science of interpreting vibration information is called vibration signature analysis. The method used in conventional vibration signature analysis is as follows (5):

> "Instantaneous mechanical motion (vibration) is converted into an electronic signal that is then analyzed, filtered, or otherwise manipulated. In mechanical vibration theory, this complex signal is the result of summing many discrete sources, each vibrating at a single frequency. Through a process called spectrum analysis, this summing effect is mathematically reversed so that the energy content at individual frequencies can be determined. Therefore, spectrum analysis helps one to identify the specific components in a machine that are vibrating."

Lower frequency testing is good for obtaining a detailed diagnostic picture of different components in a given piece of machinery, but it is not usually a good method for detecting incipient failures. Low frequency tests are often run once a problem has been detected. Higher frequency monitoring is good for detecting incipient equipment failure but is not well-suited for diagnosing what the specific problem might be. A permanent high frequency probe is often attached to a piece of machinery with an alarm to warn when abnormal vibrations occur.

4.3.6 Relief Valve Testing

Two types of tests are carried out on relief valves. In one test, the valve open and reseat pressures are measured. In another test, the capacity of the relief valve is measured. The test for determining opening and reseating pressures involves a very simple bench top apparatus that uses hydraulic pressure. The valve is pressurized with water until it opens, at which point a small amount of water is ejected and the valve closes. The opening and closing pressures are recorded. Most plant maintenance shops have this type of capability. Measuring valve capacity is a much more complicated procedure and almost always must be done at one of a few labs that is equipped for this type of test.

The opening and reseating pressures of a relief valve should be tested periodically as a part of routine maintenance. Testing a valve's capacity should be done whenever any corrosion, fouling or scaling has occurred.

4.4 OPERATING AND MAINTENANCE MANUALS

As discussed in Sections 2 and 3 of this manual, accidental chemical releases are often caused by either improper equipment or equipment failure or process operation. Good operating and maintenance practices are the key to preventing such releases. In both cases, clearly and correctly defined procedures in maintenance and operating manuals contributes to good practices.

Well-written instructions give enough information about a process that the worker with hands-on responsibility for operating or maintaining the process can do so safely, effectively, and economically. These instructions not only document day-to-day procedures, but also are the basis for most industrial training programs (7, 8). In the chemical industry, operating and maintenance manuals vary in content and detail. To some extent, this variation is a function of process type and complexity; however, in many cases it is a function of management policy. Because of their importance to the safe operation of a chemical process, these manuals must be as clear, straightforward, and complete as possible. In addition, standard procedures should be developed and documented before plant startup, and appropriate revisions should be made throughout plant operations.

Documentation of operation and maintenance procedures may be combined or documented separately. Procedures should include startup, shutdown, hazard identification, upset conditions, emergency situations, inspection and testing, and modifications (1, 2). Several authors think operating manuals should include (1, 3, 7, 8):

- Process descriptions;
- A comprehensive safety and occupational health section;
- Information regarding environmental controls;
- Detailed operating instructions;
- Sampling instructions;
- Operating documents (e.g., logs, standard calculations);
- Procedures related to hazard identification;
- Information regarding safety equipment;
- Descriptions of job responsibilities; and

- Reference materials.

Equipment sketches and process flow diagrams are a useful feature of the process descriptions included in operating manuals. Since safety and occupational health information is an integral component of operating manuals, this section should include information on the properties and hazards of materials, special precautions to prevent exposure, and spill and fume control measures (8).

Operating instructions must include those for normal operations, normal startup and shutdown (including variations based on length of shutdown), and abnormal or emergency shutdown (1). Diagnostic guides and a listing of normal (safe) operating limits specific to each type of operation should also be provided (3). Sampling instructions can include the location and identification of sampling points, sampling frequency, sampling methods, and safety precautions. Operating documents include operator's logs, manager's logs, and standard calculations. Safety equipment descriptions generally include a guide to locations, the equipment inspection schedule, and manuals for their use and maintenance. Descriptions of job responsibilities should explicitly define the operator actions expected in both routine and upset situations, and should explain who has authority over specific functions (3, 7).

Serious industrial accidents have occurred during startup and shutdown periods (2). Formal startup and shutdown procedures should be described in the operating manual or in separate but readily available documentation. Startup manuals, or manual sections, may include descriptions of the overall startup strategy, pre-startup conditions, required utilities, and material, process design, and equipment performance characteristics. Frequently this type of documentation will include checklists summarizing the sequence of steps that must be taken during startup (7,9). Hazard identification, accident prevention, and emergency actions specifically related to startup activities should also be addressed. Shutdown procedures should define practices to be used for both normal and emergency shutdown. In many instances, process facilities cannot be shut down rapidly, and tasks must be conducted in an orderly progression to avoid creating hazardous conditions. For this reason, sequential checklists summarizing activities are often included in shutdown procedures. Some of the areas typically addressed by shutdown procedures are (9):

- Cooling and depressurizing equipment;
- Pumping out vessels (particularly if vessel contain flammable, corrosive, or toxic materials);
- Purging flammable vapors; and
- Inspections and testing before entering equipment.

The potential for chemical releases during startup and shutdown activities is significant. Fittings and equipment placed on line (i.e., placed in contact with process fluids) during startup are potential leakage sources. During shutdown, operations such as purging, depressurizing, and equipment disassembly are potential chemical release sources. The potential for, prevention of, and proper response to accidental chemical releases should be specifically addressed in startup and shutdown procedures.

Upset and emergency procedures instruct workers on how to handle non-routine operations. Situations may range from operation outside the bounds defined as normal to serious situations involving fire, explosion, health hazards, or pollution episodes. Other examples of hazards for which prescribed response actions should be available include:

- Leaks of materials from equipment;
- Defective or damaged equipment;

- Detection of unusual odors or sounds;
- Abnormal conditions such as high or low temperature or pressure,
- Infractions of operating procedures or safety regulations,
- Unauthorized hazardous work, and
- Unauthorized personnel or vehicles in hazardous areas.

Maintenance manuals typically contain procedures not only for routine maintenance, but also for inspection and testing, preventive maintenance, and facility or process modifications. These procedures include specific items such as codes and supporting documentation for maintenance and modifications (e.g., permits-to-work, clearance certificates), equipment identification and location guides, inspection and lubrication schedules, information on lubricants, gaskets, valve packings and seals, maintenance stock requirements, standard repair times, equipment turnaround schedules, and specific inspection codes (e.g., for vessels and pressure systems) (2). Full documentation of the maintenance required for protective devices is a particularly important aspect of formal maintenance systems. These devices include:

- Pressure relief valves;
- Rupture discs;
- Tank vents and filters;
- Other pressure relief devices;
- Non-return valves (e.g., check valves);

- Mechanical trips and governors;
- Instrument trips; and
- Alarm, sprinkler, and fire water systems.

Maintenance manuals should also describe the way to keep equipment records. Such records are usually maintained for individual equipment items, and include identification, location, engineering descriptions, operating conditions, inspection intervals and maintenance history (2). In some instances, equipment records are incorporated as part of the maintenance manual; in others these types of records are maintained separately. These records, and the frequency with which they are reviewed, are important to release prevention because they have the data needed to evaluate equipment integrity.

The preparation of operating and maintenance manuals, their availability, and the familiarity of workers with their contents are all important to safe operations. The objective, however, is to maintain this safe practice throughout the life of the facility. Therefore, as processes and conditions are modified, documented procedures must also be modified. The written documentation used to control operating and maintenance activities on a day-to-day basis must be up-to-date and include the latest process changes. One way of ensuring that documentation is properly maintained is to institute a regular procedure review process (1, 5). This type of review is often conducted as part of facility safety audits, but can also be performed independently of total system checks. Examples of the questions often asked during procedure reviews are presented in Table 4-2.

Documented operating and maintenance procedures form the backbone of effective safety and loss prevention policy. Adherence to these procedures is the primary standard against which management judges the worker's performance in safe operations, and effort put into the preparation, maintenance, and enforcement of these procedures is a measure of management's commitment to

TABLE 4-2. EXAMPLES OF QUESTIONS ASKED DURING PROCEDURE REVIEWS

Are manuals written in a clear and concise manner?

Are they available to all operators and maintenance personnel?

Are they kept up to date and reviewed at regular intervals?

Are the documented procedures obeyed?

Are the procedures reviewed regularly with each employee?

Are emergency plans included?

Are hazards and preventative measures spelled out?

Source: Reference 1.

accident prevention. In addition, these procedures are the building blocks of training programs, of communications between operating staff and supervisors, and finally, of improved procedures.

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SECTION 5

PROTECTION TECHNOLOGIES

This section discusses the various types of technologies that may protect against the incipient accidental air release of a toxic chemical. Protection technologies, as defined in this manual, apply when the chemical is still contained; it has escaped from its primary containment but has not yet escaped to the atmosphere. An example of an incipient accidental release is a relief valve discharge still contained within its manifold piping. The technology of protection involves equipment and systems that capture or destroy a toxic chemical before it is released to the environment. Protection technologies include the following:

- Flares,
- Scrubbers, and
- Enclosures.

Each of these technologies represents an add-on to the basic process system it protects. Flares and scrubbers are technologies in common use for ordinary pollution control with many well-developed applications. In the context of accidental toxic chemical releases, however, there are special design problems and considerations that may differ from the applications of these technologies to ordinary process or vent streams. An enclosure provides temporary containment of a released chemical until it can be released to the atmosphere at a controlled, non-threathening rate or treated by one of the other technologies discussed above. While the purpose of the first two protection technologies is to reduce the quantity of chemical ultimately released, enclosures control the rate of release to the atmosphere or to treatment technology.

The appropriate application and proper design of these systems for toxic chemicals must be evaluated on a case-by-case basis. At present, a major limitation of both applicability and design are that fundamental design and performance data under the severe and unstable operating conditions encountered in an emergency are not well developed. The basic characteristics of flares and scrubbers, including a brief process description and a discussion of the applicability of the technique, performance, and typical costs, are discussed below.

5.1 FLARES

Flares are devices routinely used in the chemical process industries to burn intermittent or emergency emissions of flammable waste gases. Sources of such emissions are generally process vessels. Flares are distinguished from other process combustion devices such as incinerators by their design to handle extreme flow rate variations and their unenclosed combustion zone. A flare is basically a stack which burns a flammable gas at the discharge.

5.1.1 Process Description

A total flare system consists of collection piping, a seal pot, a liquid knock-out vessel, and the flare itself. Figure 5-1 is a conceptual illustration of a typical flare system. The flare is a section of vertical piping with a specially designed combustion tip. The tip consists of a pilot light to ignite flammable gases flowing out the end of the flare pipe. Tip designs vary according to the specific application and are an important aspect of flare design. The system shown in the figure is for an elevated flare.

Two basic types of flares are elevated flares and ground flares. Figure 5-2 shows a typical ground flare. Elevated flares are long vertical pipes which may range to heights as great as 600 feet, while ground flares usually do not exceed 150 feet in height (1). Ground flares are generally surrounded by a refractory enclosure. Elevated flares are usually designed to handle larger flows than ground flares, and is more likely to be used for high volume upset or emergency flaring situations. The ground flare is more likely to be

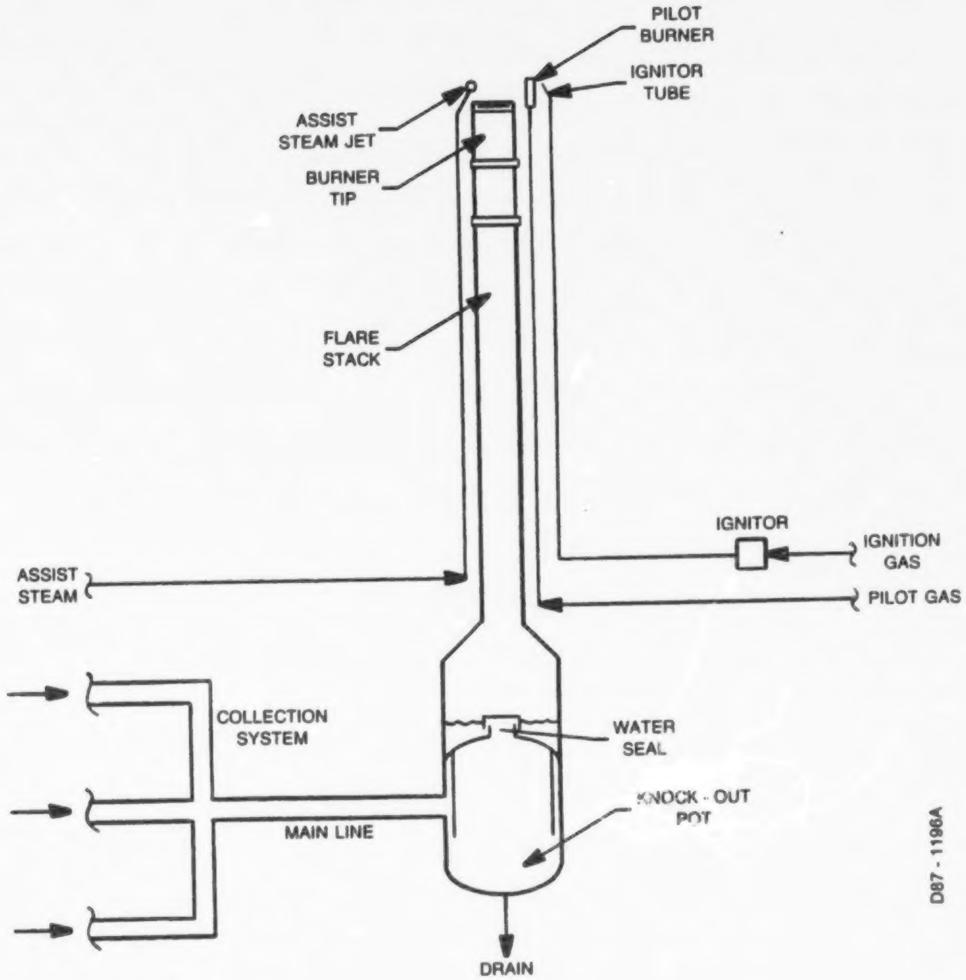
PILOT BURNER
IGNITOR TUBE
ASSIST STEAM JET
BURNER TIP
FLARE STACK
IGNITOR
IGNITION GAS
ASSIST STEAM
PILOT GAS
COLLECTION SYSTEM
WATER SEAL
KNOCK - OUT POT
MAIN LINE
DRAIN
D87 - 1196A

Figure 5-1. Conceptual diagram of elevated flare system (steam assisted).

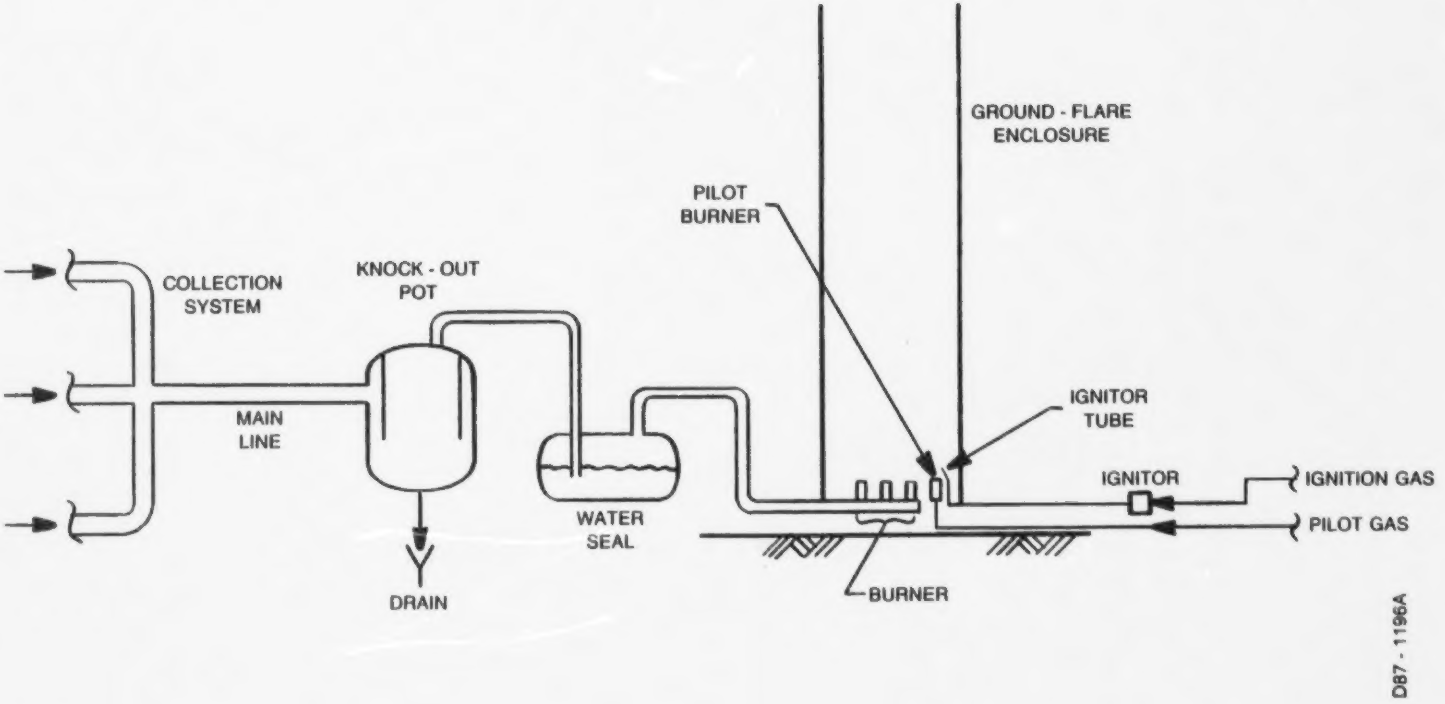
GROUND - FLARE
ENCLOSURE
PILOT
BURNER
COLLECTION
SYSTEM
KNOCK - OUT
POT
MAIN
LINE
IGNITOR
TUBE
IGNITOR
IGNITION GAS
PILOT GAS
WATER
SEAL
DRAIN
BURNER
D87 - 1196A

Figure 5-2. Conceptual diagram of ground flare system.

used for smaller volume, routine process venting. Elevated flares may be more common, however. A survey of 21 petroleum refineries in California indicated that elevated flares made up 87 per cent of the total (1).

Gases are collected through the collection piping and routed to the flare. The collection piping consists of two basic parts: the main flare line and lateral lines to individual process units or vessels. Proper operation of a flare system depends on sizing the collection system to accommodate possible simultaneous discharges of different processes at different pressures into the flare system under widely varying flow rates. Pressure drop considerations in different parts of the collection system are, therefore, quite important. The maximum allowable line pressure is limited by the lowest pressure relief valve discharging into the collection system.

A seal pot is often installed between the collection piping and the flare. This water seal maintains some positive pressure on the flare piping collection system when there is no discharge in order to prevent backflow from the flare into the collection system. Its primary purpose is to prevent air from getting into the collection piping. Some systems use mechanical air restriction seals.

A knockout drum is used between the collection piping and the flare stack to prevent liquid hydrocarbons entrained with the gas from entering the flare. Entrained liquid or solid particles may not totally burn which would degrade flare performance or even cause a "raining" fire.

Other features of flares include air or steam injection at the flare type to ensure smokeless operation, and the use of a purge gas flow at low flow rates to maintain gas velocity and ensure flame stability.

5.1.2 Applicability

Flares may be applicable as protection against accidental releases of toxic chemicals when the release is initially contained within piping or ducting or can be routed to the same, for example, from a release within a building, and when the toxic chemical is also combustible. The heating value of the chemical must be sufficient to ensure its combustion at flare temperature conditions.

Basic design requirements for flares burning toxic chemicals are:

- The ability to operate safely over a wide range of flow rates and varying compositions,
- Have acceptable emissions of radiant heat and noise, and
- Achieve acceptable destruction efficiency for the toxic chemical.

Flow rates for flares are highly variable because flare systems are designed for intermittent routine process or upset and emergency venting. Compositions vary because gases are usually controlled from multiple sources within a process facility. Elevated flares, which are used for higher capacities than ground flares, are designed with capacities as high as 2 million pounds per hour with turn-down ratios of as much as a thousand. There are estimates that over 95 per cent of the time, these flares operate at less than five per cent capacity (2). The ability of flares to accommodate large variations in flow rate is an important consideration in using them for protection against accidental chemical releases. Depending on the size of a flare relative to a potential release, the accidental release flow rate may constitute a large or small fraction of the total flare flow rate and, correspondingly, could have a significant or relatively minor effect on the instantaneous total flow rate and flare performance. For example, in a dedicated flare system, where the accidental release would constitute the entire flow, significant variability and performance fluctuations could occur. In a large shared flare system, on the other hand, the accidental release flow might not have a large effect on variability and performance if it is a small fraction of the total flow.

Whether a dedicated flare or shared flare is used depends on site specific considerations. A shared flare may be advantageous for several reasons. A dedicated flare system for infrequent emergency use may be difficult to safely maintain in full working condition. A shared flare may allow connection to an existing system. With a shared flare, however, design for emergency conditions must ensure that a large release of toxic gas does not overwhelm the flare and lead to flame blowout, or that the pressure from the toxic emergency release does not cause a backflow into other process units tied into the flare collection piping.

The primary compositional requirement of flares is that the vented gases are easily ignitable and have adequate heating value to minimize supplementary fuel requirements.

A fundamental flare design variable is exit velocity. Typical flare exit velocities range from 0.2 to 400 ft/sec. Excessive exit velocities cause flame detachment from the burner tip or flare quenching (flame-out). A typical limiting exit velocity is 400 ft/sec or less, depending on the heat content of the flare gas. This criterion has been recommended by the EPA to ensure 98 percent destruction efficiency of flared chemicals using a steam-assisted flare (3). The addition of an accidental release discharge to an existing flare must not cause this maximum flow to be exceeded. The normal maximum gas flow is determined by an inventory of all contributors to the gas collection system and an analysis of the probability of various streams venting simultaneously. From this total flow and from the maximum velocity limitation the flare diameter can be calculated. The diameter of commercial flares varies from several inches to about 3 feet.

Empirical correlations have been developed for sizing the remaining flare components. Flame length can be estimated from the gas molecular weight (which is related to heat content), temperature, and flow rate. The flame length, combined with limitations on allowable heat radiation to personnel and equipment, is used to determine the height of the flare and the required clear area around the base. Numerous references present these calculations (4,5,6).

Two other important design considerations for flares include air infiltration and flashback. Water seals or mechanical seals are two means used to prevent these conditions. At low process flows a purge gas may be used to maintain adequate flow for proper flare operation. In a dedicated flare it might even be necessary to maintain a slight positive nitrogen pressure on the system to preclude air infiltration.

An existing flare system collects vent gases from process units as needed, as well as emissions from pressure relief valves and other emergency-generated sources. Some units may not be tied into the flare system for any of several reasons. If a process unit does not require periodic normal venting or in an old facility relief valves may vent directly to the atmosphere. Certain precautions should be observed when connecting multiple discharges to a flare system. The precautions are avoidance of incompatible chemicals, corrosive materials, and chemicals prone to fouling. Concern for these chemical characteristics is significantly greater in a chemical plant than in a petroleum refinery where much traditional experience on flaring is based.

For example, some processes in chemical plants contain oxygen in the vent stream. Releasing hot gases containing oxygen into a fuel-rich mixture could create a flashback or explosion. Similar results could occur with other mutually reactive materials.

Besides these incompatibilities between gases, fouling caused by venting a polymerization reaction or other viscous substance into the collection network could occur. Plugging could eventually cause a high back pressure in the collection system, preventing relief valves from functioning properly. Organic liquids entering the flare could overload the knockout drums and create rain fires. Low vapor pressure liquids could flash, condensing and freezing water vapor in the line, which would cause high back pressure.

Another concern is corrosion of the pipe network, which is normally made of mild steel. Chlorides and acids are detrimental, although this is not a critical concern in an emergency situation.

accidental release could damage the pipes or potentially affect the venting of other process units. Table 5-1 summarizes the factors that need to be considered to prevent accidental chemical releases when using a flare system.

5.1.3 Control Effectiveness

Flaring protects against accidental toxic chemical releases by reducing the quantity of toxic chemical released. This reduces the overall consequences of the release. Ideally a flare would destroy all of the toxic chemical so none would be released. It is difficult to estimate the destruction and removal efficiency (DRE) of flares because of the many variables associated with their operation. Numerous studies have been conducted to determine the operational performance of flares. EPA has published a set of flare requirements that are meant to ensure 98 percent or greater destruction of the gases (3). These requirements include a gas heating value of at least 900 Btu/scf and a maximum gas velocity related to the heating value. In an emergency condition, however, these conditions might not be met. For example, a large release of carbon tetrachloride could significantly reduce the lower heating value of the flare gas since carbon tetrachloride is nonflammable. A screening study on some 25-30 compounds performed on 1/16 and 1/8 inch diameter test flares generally obtained over 99 percent destruction efficiency except for high concentrations of carbon monoxide and ammonia (7). A 100 ppm hydrogen cyanide stream was only 85 percent controlled.

It is difficult to measure the efficiency of an operating flare because of the intense heat and the instability of the flame. Even pilot scale facilities encounter these difficulties. A properly run elevated flare uses steam or forced air to increase turbulence and allow complete combustion. The gas flow can vary instantaneously, and since the flame life is 2-3 seconds, steady state conditions are reached very quickly. As long as the accidental released toxic is combustible and the volumetric rate does not exceed the capacity of the flare nozzle, one would expect a high DRE.

In the case of noncombustible vapors, the use of a flare would dramatically increase the dispersion. The gas velocity in the flare of up to 400

TABLE 5-1. IMPORTANT CONSIDERATIONS FOR USING FLARES TO PREVENT ACCIDENTAL CHEMICAL RELEASES

- Maximum flow rate - will it cause a flame blowout?
- Possibility of air, oxygen, or other oxidant entering system?
- Is gas combustible - will it smother the flare?
- Will any reactions occur in collection system?
- Can liquids enter the collection system?
- Will liquids flash and freeze, overload knockout drum or cause rain fire?
- Is the back pressure of the collection system dangerous to the releasing vessel?
- Is releasing vessel gas pressure or temperature dangerous to collection system?
- Will acids or salts enter the collection system?
- Will release go to an enclosed ground or to an elevated flare?
- If toxic is not destroyed, what are the effects on surrounding community?

steam or forced air to increase turbulence and allow complete combustion. The gas flow can vary instantaneously, and since the flame life is 2-3 seconds, steady state conditions are reached very quickly. As long as the accidental released toxic is combustible and the volumetric rate does not exceed the capacity of the flare nozzle, one would expect a high DRE.

In the case of noncombustible vapors, the use of a flare would dramatically increase the dispersion. The gas velocity in the flare of up to 400 feet per second associated with the buoyancy of the thermal plume could easily dilute ambient concentrations by several orders of magnitude. Some noncombustible compounds could possibly undergo a pyrolysis reaction in the oxygen-lean portion of the flame, especially if hydrogen is present.

Because of the variable flow capacity, high temperature, high gas velocity, and usual remote locations, using a flare to prevent accidental chemical releases can be a highly effective technique. Small or isolated vessels that contain a process that does not require normal venting of a flammable gas, and that employ relief valves and rupture disks which may have never been used, can be connected to a flare system to prevent accidental releases.

The number of potential hazards associated with flaring include:

- Explosions in the system;
- Obstruction in the system;
- Low temperature embrittlement of the pipework;
- Heat radiation from the flame;
- Liquid carry over from the flare; and
- Emission of toxic materials from the flare.

In designing and operating a flare system, precautions must be taken to prevent these hazards from occurring. A rigorous examination of all probable accident conditions should be performed with respect to the hazards listed above to ensure that using a flare system to prevent accidental chemical releases does not create a greater environmental hazard.

5.1.4 Costs of Flare Systems

As protection systems, flares have relatively low capital costs. Elevated flares, constructed mainly of pipe, are very inexpensive. The flare tip has a special design for efficient steam, air and fuel mixing. Enclosed ground flares are an order of magnitude more expensive because of the numerous burner nozzles, refractory material, acoustical insulation, etc.

The operating costs of elevated flares, however, are high because of the need for a purge gas and steam injection. Enclosed flares have much smaller pilot and purge gas difference becomes a significant factor, which explains the use of ground flares for normal process flaring in conjunction with an elevated flare for emergencies.

Table 5-2 compares the costs (1986 dollars) of elevated and ground level flares (8). The costs of two applications are presented, ethylene waste gas, and a low-Btu waste gas. As can be seen, initial costs for the elevated flare are significantly lower than for the the ground flare. Costs for connecting a new source to an existing flare system would depend primarily on the piping and engineering costs for the modification. The capital cost of the elevated system is only moderately sensitive to flowrate. The operating costs, however, for the elevated flare are proportional to the flowrate. The operating costs of the ground fare depend little on size. The costs presented in the table do not include costs for the collection system, which could easily exceed the flare cost. Also, the design basis for the systems in this table may not meet recently promulgated EPA requirements for a fuel gas heat content minimum of 300 Btu/scf. This requirement could raise the operating costs presented for the low-Btu waste gas example.

TABLE 5-2. COST COMPARISON OF ELEVATED AND ENCLOSED GROUND FLARING SYSTEMS (May 1986 Dollars)

Waste Gas Flow Rate, lb/hr	Flare-Tip Diameter, in.	Capital Cost* ($)	Total Annual Cost ($/yr)	Capital Cost ($)	Total Annual Cost ($/yr)
I. Systems designed for smokeless flaring of high-Btu (ethylene) waste gases**					
	3	8,000	16,000	30,000	980
25,000	8	20,000	150,000	100,000	1,500
250,000	24	50,000	1,450,000	450,000	3,200
II. Systems designed for flaring of low-Btu waste gases***					
		pilots, purge and assist gas			pilots and purge (no assist gas)
2,500	3	8,000	6,500	8,000	980
25,000	8	14,000	52,000	26,000	1,500
250,000	24	26,000	480,000	60,000	3,200

* Complete elevated flaring system with stack of sufficient height to ensure maximum grade-level radiation of 1,500 Btu/hr/ft^2, ladders and platforms are all painted and ready for erection.

** Operating costs are based on 10 percent running time for flaring ethylene waste gases with continuous natural gas pilots and continuous natural gas purge at \$2.00/1000 ft^3, steam at \$0.02/lb.

*** Operating costs are based on 10 percent running time for flaring low-Btu/ft^3 and molecular weight of 24-with natural gas pilots, continuous purge and assist gas at \$2.00/1000 ft^3.

Source: Adapted from Reference 8.

5.2 SCRUBBERS

Absorption is the transfer of a soluble (or vapor) into a relatively nonvolatile liquid. Absorption of a gas or vapor by a liquid can be physical only, or can result in a chemical reaction. Regardless of the absorption mechanism, intimate mixing of the gas and liquid is needed to achieve a high absorption efficiency.

Scrubbers or gas absorbers that remove both organic and inorganic compounds from gas streams are routinely used in many process facilities for raw material and/or product recovery and as air pollution control devices (9). There are several standard types as well as special designs for specific applications. Scrubbers can be used in some situations to control emergency releases of toxic chemicals if they are properly designed and operated.

5.2.1 Process Description

Mass transfer equations that describe the absorption process have been presented in numerous other works and are not shown here (10,11,12). The removal efficiency of a gas is a complex function of equilibrium-related factors (temperature, pressure, gas phase concentration, liquid phase composition) and kinetic factors (gas-liquid interfacial area, contact time, liquid and gas rates, etc.). In general, the removal effectiveness of a gas by absorption can be estimated from the vapor pressure of the gas at equilibrium with the gas in the liquid. If the gas equilibrium vapor pressure of the gas is low, the gas can be readily absorbed in a properly designed system.

As protection devices for accidental chemical releases, scrubbers can be used to control toxic gas releases from emergency vents and pressure relief discharges from process equipment or vents from secondary containment enclosures. All scrubbers require a liquid feed system and some type of contacting mechanism to provide high surface area contact between the gas and liquid. A schematic of common absorber types is shown in Figure 5-3. The internals of column or tower absorbers vary with with application. Formed packings of

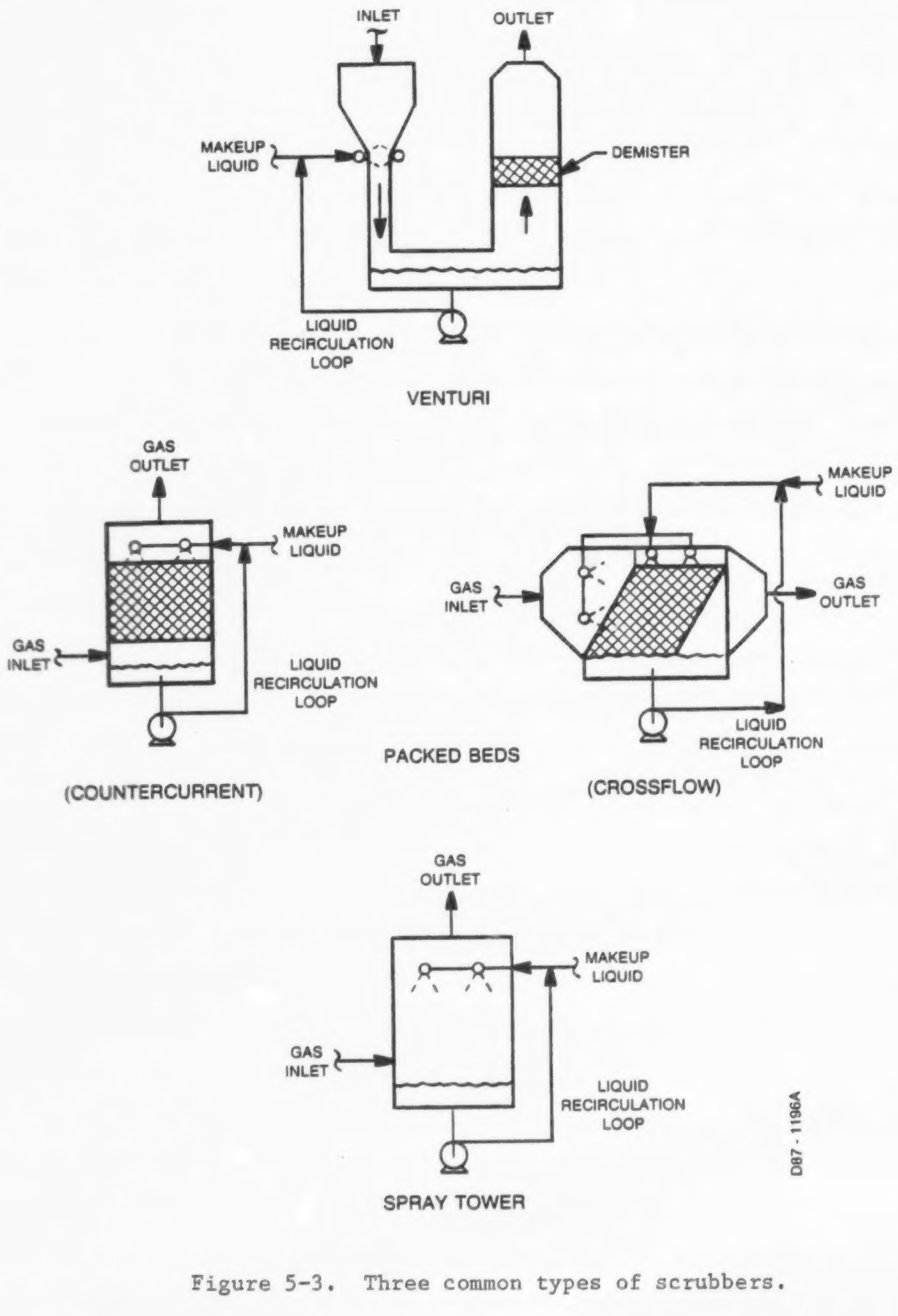
INLET
OUTLET
MAKEUP LIQUID
DEMISTER
LIQUID RECIRCULATION LOOP
VENTURI
GAS OUTLET
MAKEUP LIQUID
GAS INLET
LIQUID RECIRCULATION LOOP
(COUNTERCURRENT)
PACKED BEDS
MAKEUP LIQUID
GAS INLET
GAS OUTLET
LIQUID RECIRCULATION LOOP
(CROSSFLOW)
GAS OUTLET
MAKEUP LIQUID
GAS INLET
LIQUID RECIRCULATION LOOP
SPRAY TOWER
D87 - 1196A

Figure 5-3. Three common types of scrubbers.

plastic and other materials, perforated trays, valve trays, and open columns with spray nozzles have all been used. The types of absorbers most applicable to accidental chemical releases are probably spray towers, packed towers, and venturis. Spray towers have the advantage of low pressure drop and high liquid-to-gas (L/G) ratios, but the disadvantage of low efficiencies. The open spray tower is used to reduce plugging problems for liquids that may contain solids. The other tower internals are used with clean liquids. Venturis have the advantage of simplicity, but the disadvantage of high backpressure and limited removal efficiencies. Packed towers have higher efficiencies than spray towers but limited L/G ratios and a moderate backpressure. Selection of specific tower internals is based on trade-offs between the surface area for mass transfer and gas side pressure drop. Vendors are continually striving to develop high area packings with low pressure drop characteristics.

The size of an absorber is determined by flow rate, the gas-liquid system involved, and the removal efficiency required. Flow rate determines diameter, (or cross-sectional area) and the specific system and removal efficiency determine the height (or time in the contact zone) of an absorber. In general for packed beds or spray towers, the gas velocity is limited to a maximum of about 10 feet per second, which establishes the diameter for a given flow rate. The liquid rate is set based on the L/G ratio required to achieve a specific removal rate for the particular gas and solvent combination.

5.2.2 Applicability

In general, absorbers are appropriate for protecting against accidental releases of toxic chemicals when the substance released is readily soluble in some non-flammable absorbing medium, and the size of the release allows an economically reasonable scrubber size.

As discussed earlier, an absorber is sized to handle certain flow rates. Significant variations in the flow can cause severe operating problems. High gas rates cause flooding, weeping, and pressure surges in the column. The flow characteristics of the accidental release may be steady or it may be a sudden surge load on the absorber. The absorber must be designed to accommodate these operational demands. Absorbers for emergency relief applications typically operate under a slight positive pressure. A high pressure gas surge beyond the absorber vessel design pressure could damage the vessel. The absorber must also be designed so that the pressure drop does not create a backpressure that would cause a destructive overpressure at the source of release. Such an occurrence would cause a greater release than the one the scrubber was trying to prevent. Additionally, scrubbers must be designed to accommodate hot gases, or those that generate heat when absorbed, to prevent thermal damage to the absorber, vessel liner, or other equipment.

In the event of an accidental release, the concentration of the gas being absorbed could be much higher than typically encountered in most industrial applications. Scrubbers designed specifically for emergency discharges will have taken this into account. Ordinary vent scrubbers may not be able to handle the high inlet gas concentrations. For some gases, absorption is an exothermic reaction. At high concentrations and flow rates, the heat generated may be sufficient to boil all of the scrubbing liquid, which could damage the internals (if plastic), or perhaps cause a fire.

Another consideration is the selection of scrubbing solution. Both aqueous and organic solutions can be used as absorbents. The absorbent selected depends on the absorption characteristics of the toxic material being absorbed. For example, while water may be satisfactory for hydrogen chloride, an alkaline solution is required for substantial removal of chlorine form a gas stream. It might be possible to use organic liquids in some situations as long as they are not flammable or toxic.

Compared with a flare system, which may handle waste gases from multiple sources, absorbers are often dedicated to specific units. Total plant capacity absorbers are not common because of the diverse nature of gas contaminants and the poor turndown ratio of absorbers. A typical turndown ratio is about 10:1. Also, absorbers are not readily adapted to handling flammable gases.

Absorbers generate waste material in the form of blowdown liquids and solids. Even the regenerable systems require periodic replacement of the scrubbing solution as it degrades and loses activity. The wastes may be hazardous, depending on the contamination present in these streams, which is another disadvantage when absorber systems are compared to flares. However, for infrequent emergency use these disadvantages may not be critical.

5.2.3 Control Effectiveness

The ability of an absorber to remove contaminants from gas streams is a function of the parameters discussed previously. Absorbers in process applications or pollution control with steady flow rates and constant compositions are capable of very efficient control. The effectiveness of a scrubber for protecting against accidental releases depends on whether it is dedicated to the emergency system or is used continuously with an emergency tie-in. In general, unless the occurrence of an accidental release significantly changes the composition and flow rate of a gas normally being scrubber, the performance of the non-dedicated absorber during a release incident would be expected to diminish only slightly. As long as the liquid phase chemistry is not disturbed, absorption should reduce the effects of an accidental release. For critical applications, dedicated scrubbers are preferable to common scrubber units.

As an indicator of the performance capabilities of scrubbers in typical industrial applications, Table 5-3 shows the removal efficiencies for various organic compounds and solutions. As can be seen, most of the compounds are effectively controlled. These types of efficiencies are for commercial scrubbers where economics may be limiting the efficiency feasible for long term operation. For emergency scrubbers, very high efficiencies may be achievable that would not be economical for sustained, long-term operation. Many other compounds, including H_2S, HCl, SO_3, Cl_2, SO_2, NH_3, and other inorganics, can also be removed effectively by absorption. Properly designed absorbers are capable of economically removing over 90% of these compounds. Operating costs usually limit the efficiency that is economically feasible for long-term operation. For an emergency scrubber, where intermittent use makes

TABLE 5-3. SUMMARY OF SELECTED TYPICAL COMMERCIAL ABSORPTION EFFICIENCIES FOR VARIOUS INDUSTRIAL CHEMICALS

Compound	Scrubbing Liquid	% Control Efficiency
Acetone/phenol	water	97
Acrylonitrile	water	99
Aniline	dilute sulfuric acid	99.4
Chloroprene	oil	100
Chloroprene/neoprene	oil	97
Cyclohexanol/cyclohexanone	oil	99
Formaldehyde	water	74
Methyl chloroform	water	90
Nitrobenzene	water	99+
Per/tri-chloroethylene	water	90
Terephthalic acid	water	95.6
Dimethyl terephthalate	xylene	97
Toluene diisocyante	water	60
Toluene diisocyante	caustic solution	98

Source: Reference 13

operating cost considerations less important a very high efficiency may be feasible.

Table 5-4 provides an example of the physical size and control capabilities of a scrubber for a hypothetical 50% ammonia stream. For a highly soluble gas like ammonia, relatively high efficiencies appear to be achievable in a "reasonably" sized system.

5.2.4 Costs

For a given application, the cost of a scrubber system depends primarily on the size, as determined by flow rate and removal efficiency required. Materials of construction based on corrosivity and pressure conditions also determine costs. Specific items included in the system battery limits can vary between applications. These include ductwork, fans or compressors, scrubber internals, reagent feed systems, instrumentation requirements, and degree of redundancy. Without considering a specific application, it is impossible to present a system cost. Total capital costs (including installation, indirect costs, and other fees) for absorber vessels have been presented in the literature in terms of column weight (14). The weight is related to the length and diameter of the absorber. The developed correlation was presented on a log-log graph. The data convert to the following equation:

$$\log (\text{June 1981 \$}) = 0.89 * \log (\text{column weight, lbs}) + 0.62$$

This corresponds to about $64,000 for a 5,000 pound column and does not include packing, platforms, ladders, ducting, fans, or other equipment. It does include face piping, some instrumentation, painting and insulation.

Operating costs of absorbers are highly variable. They are affected by the type of system and the reagents consumed. Tail end absorbers often produce throwaway materials which cause high reagent costs. The regenerable systems, although they recycle chemicals, incur costs for the regeneration step in the form of steam, reducing gases, or other commodities. Some costs are also associated with pumping the liquid through the column and fans or

TABLE 5-4. EXAMPLE OF PERFORMANCE CHARACTERISTICS FOR A PACKED BED SCRUBBER

Basis: Inlet stream of 50% NH_3 in 50% air. Constant gas flow per unit cross-sectional area of 455 scfm/ft^2.

Packing: 2 inch plastic Intalox® saddles.

Pressure Drop: 0.5 inch water column

Removal Efficiency, %	50	90
Liquid to Gas Ratio (gal/thousand scf)		
-- at flooding	160	160
-- operating	80	80
Packed Height, ft.	3.1	11.4

Column Diameter and Corresponding Gas Flow Rates for Both Removal Efficiencies

Column Diameter (ft)	Flow Rate (scfm)
0.5	90
1.0	360
2.0	1,400
6.3	14,000

compressors to move the gas. Absorbers typically generate a gas side pressure drop on the order of 0.1 to 0.3 psi. Venturi absorbers can have pressure drops as high as 3 psi, depending on Venturi throat size and L/G ratios.

For emergency scrubbers, which are used rarely except for periodic testing, operating costs other than maintenance are not particularly important. Selection of a specific system will be determined primarily by the performance and capital cost.

5.3 ENCLOSURES

Enclosing equipment and vessels that store or process toxic chemical are another way of preventing or decreasing the effects of an accidental chemical release. Enclosures are containment structures that capture toxic chemicals spilled or vented from storage or process equipment, thereby preventing immediate discharge to the environment. The enclosures contain the spilled liquid or gas until it can be transferred to other containment, discharged at a controlled rate that would not be injurious to people or to the environment, or transferred at a controlled rate to a flare or scrubber. While enclosures may offer some protection, there may also be disadvantages or secondary hazards, which are discussed below.

5.3.1 Process Description

Enclosures can be constructed around individual equipment items, process units, and entire plants, depending on the nature of the hazard being controlled. For example, many facilities using solvents might vent all of the air in the manufacturing building through an activated carbon system. In laboratories and other small-scale facilities, small absorbers or filters may be used on the exhaust gases. These type of systems are effective in controlling smaller emissions of toxic compounds in a normal atmosphere.

Reaction vessels may also be enclosed in buildings. However, several factors should be considered in the design of such enclosures, including potential flammability and explosive hazards. Pressures over 5 psi are capable of destroying conventional buildings.

Another enclosure scheme is to use underground storage tanks. Although it is not common practice to bury pressure vessels, many tanks containing volatile liquids are underground. The overburden acts as an effective damper on emissions from such tanks. The use of underground storage tanks for preventing a sudden release of toxic chemicals is an attractive concept. Regulations concerning the design and operation of underground tanks for hazardous wastes are designed to prevent any release to the environment (15). Although regulations have not been promulgated for hazardous products, the same concern would be expected. These requirements are discussed further below.

5.3.2 Applicability

Enclosures are useful for preventing the release of small amounts of a toxic chemical because an enclosure can temporarily contain the chemical while it is vented at a controlled rate to a control device (see protection technologies) suitable for removing the chemical from the vented stream. A secondary hazard is explosion. Enclosures must be used with caution, however. For example, a small leak of a flammable vapor in an enclosure could be concentrated to the LEL, causing an explosion if a ventilation system is not properly designed. Also, the rupture of a pressure vessel within an enclosure could overpressurize the enclosure, resulting in it destruction. When enclosures are considered for reducing the potential of an accidental release, safety aspects must be carefully reviewed to prevent greater hazards. Enclosures are more appropriate for non-flammable toxic chemicals than for toxic ones.

A modified form of enclosure is the underground storage tank. Hazardous product and reactants stored in underground tanks will have to conform to regulations for these tanks. Such tanks require approved secondary containment which include external liners, vaults, and double wall tanks (15). For tanks of hazardous waste substances currently regulated, monitors capable of detecting a leak within 24 hours must be used, and all underground piping must be double walled. Additional requirements are specified for ignitable, reactive, and incompatible wastes in Part 264.198 and 199. Regulations governing release detection, prevention, and correction are expected in the near future. Congress has specified the following dates by which EPA regulations must be promulgated for underground tanks (16):

- February 9, 1987 - regulations for existing and new petroleum tanks
- August 9, 1987 - regulations for new hazardous chemical product tanks
- August 9, 1988 - regulations for existing hazardous chemical product tanks

5.3.3 Control Effectiveness

Enclosures may be a very effective means of controlling accidental releases. Depending on the type and design of the enclosure, emissions could be almost totally controlled since they could be confined until vented to a destruction or capture device such as a flare or scrubber. These types of systems are used to control exothermic reactions that use pyrophoric reactants (17).

The effectiveness of enclosures may be compromised by two things: flammable materials and pressurized vessels. With flammable materials, enclosures can create a secondary hazard both without and with an accidental release. During routine operations, small leaks of a flammable substance in an enclosed area can lead to the accumulation of a flammable vapor-air mixture which, if ignited, could damage the enclosure and process equipment, thus causing the catastrophe it was intended to prevent. Proper ventilation could reduce this hazard. During a release, a properly designed enclosure should be effective if the release occurs at a low to moderate rate. A sudden release from a pressurized vessel, however, could overpressure the enclosure itself, causing damage and releasing the chemical. The enclosure would have served no causing damage and releasing the chemical. The enclosure would have served no purpose. Because the sudden catastrophic failure is less likely than a large uncontrolled leak, however, an enclosure still might be appropriate if designed with appropriate explosion relief venting.

5.3.4 Costs

The variety of enclosures that can be used makes it difficult to estimate their costs. Total containment systems can exceed the cost of the controlled vessel, since they must be larger than the vessel and still be designed to meet the same criteria. Costs for buildings with directed ventilation systems can be estimated easily; however, a total cost can not be assigned to the control system. Small enclosures around process vessels or equipment can also vary in cost because of safety considerations (explosion risk, temperature limitations, atmosphere requirements, etc.). Additional costs are associated with the cleanup equipment needed when the enclosure becomes contaminated.

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APPENDIX A
GLOSSARY

This glossary defines selected terms used in the text of this manual which might be unfamiliar to some users or which might be used differently by different authors.

Accidental release: The unintentional spilling, leaking, pumping, purging, emitting, emptying, discharging, escaping, dumping, or disposing of a toxic material into the environment in a manner that is not in compliance with a plant's federal, state, or local environmental permits and results in toxic concentrations in the air that are a potential health threat to the surrounding community.

Alkane: A chemical compound consisting only of carbon and hydrogen in which the carbon atoms are joined to each other by single bonds.

Assessment: The process whereby the hazards which have been identified are evaluated in order to provide an estimate for the level of risk.

Autocatalytic: A chemical reaction which is catalyzed by one of the products of the reaction.

Carcinogen: A cancer causing substance.

Containment/Control: A system to which toxic emissions from safety relief discharges are routed to be controlled. A caustic scrubber and/or flare can be containment/control devices. These systems may serve the dual function of destructing continuous process exhaust gas emissions.

Contingency Plan: A plan which describes the actions that facility personnel will take to minimize the hazards to human health or the environment from fires, explosions or accidental releases of hazardous materials.

Control System: A system designed to automatically maintain all controlled process variables within a prescribed range.

Creative Checklist: A list of major hazards and nuisances designed so that when an individual item from the list is associated with a particular material or a significant part of a unit, an image of a specific hazard or nuisance is generated as a stimulus to the imagination of members of a multidisciplinary team.

Creative Checklist Hazard and Operability Study: A Hazard and Operability Study which uses a Creative Checklist to stimulate a systematic, yet creative search for hazards.

Emergency Response Plan: A plan of action to be followed by source operators after a toxic substance has been accidentally released to the atmosphere. The plan includes notification of authorities and impacted population zones, minimizing the quantity of the discharge, etc.

Event Tree: A logic diagram which depicts all pathways (success and failure) originating from an initiating event.

Exothermic: A term used to characterize the evolution of heat. Specifically refers to chemical reactions from which heat is evolved.

Facility: A location at which a process or set of processes are used to produce, refine or repackage chemicals, or a location where a large enough inventory of chemicals are stored so that a significant accidental release of a toxic chemical is possible.

Fault Tree: A logic diagram which depicts the interrelationships of various primary events and subevents to an undesired top event.

Fire Monitor: A mechanical device holding a rotating nozzle, which emits a stream of water for use in firefighting. Fire monitors may be fixed in place or may be portable. A fire monitor allows one person to direct water on a fire whereas a hose of the same flowrate would require more than one person.

Guide Word Hazard and Operability Study: A Hazard and Operability Study which uses Guide Words to stimulate a systematic yet creative search for hazards.

Hazard: A source of danger. The potential for death, injury or other forms of damage to life and property.

Hazard and Operability Study: The application of a formal systematic critical examination to the process and engineering intentions of the new facilities to assess the hazard potential of maloperation of individual items of equipment and the consequential effects on the facility as a whole.

Hygroscopic: Readily taking up and retaining moisutre (water).

Identification: The recognition of a situation, its causes and consequences relating to a defined potential, e.g. Hazard Identification.

Lachrymator: A substance which increases the flow of tears.

Mitigation: Any measure taken to reduce the severity of the adverse effects associated with the accidental release of a hazardous chemical.

Mutagen: An agent that causes biological mutation.

Plant: A location at which a process or set of processes are used to produce, refine, or repackage, chemicals.

Prevention: Design and operating measures applied to a process to ensure that primary containment of toxic chemicals is maintained. Primary containment means confinement of toxic chemicals within the equipment intended for normal operating conditions.

Primary Containment: The containment provided by the piping, vessels and machinery used in a facility for handling chemicals under normal operating conditions.

Probability/potential: A measure, either qualitative or quantitative, that an event will occur within some unit of time.

Process: The sequence of physical and chemical operations for the production, refining, repackaging or storage of chemicals.

Process machinery: Process equipment, such as pumps, compressors, heaters, or agitators, that would not be categorized as piping and vessels.

Protection: Measures taken to capture or destroy a toxic chemical that has breached primary containment, but before an uncontrolled release to the environment has occurred.

Pyrophoric: A substance that spontaneously ignites in air at or below room temperature without supply of heat, friction, or shock.

Qualitative Evaluation: Assessing the risk of an accidental release at a facility in relative terms; the end result of the assessment being a verbal description of the risk.

Quantitative Evaluation: Assessing the risk of an accidental release at a facility in numerical terms; the end result of the assessment being some type of number reflects risk, such as faults per year or mean time between failure.

Reactivity: The ability of one chemical to undergo a chemical reaction with another chemical. Reactivity of one chemical is always measured in reference to the potential for reaction with itself or with another chemical. A chemical is sometimes said to be "reactive", or have high "reactivity", without reference to another chemical. Usually this means that the chemical has the ability to react with common materials such as water, or common materials of construction such as carbon steel.

Redundancy: For control systems, redundancy is the presence of a second piece of control equipment where only one would be required. The second piece of equipment is installed to act as a backup in the event that the primary piece of equipment fails. Redundant equipment can be installed to backup all or selected portions of a control system.

Risk: The probability that a hazard may be realized at any specified level in a given span of time.

Secondary Containment: Process equipment specifically designed to contain material that has breached primary containment before the material is released to the environment and becomes an accidental release. A vent duct and scrubber that are attached to the outlet of a pressure relief device are examples of secondary containment.

Teratogenic: Causing anomalies of formation or development.

Toxicity: A measure of the adverse health effects of exposure to a chemical.

APPENDIX B

TABLE B-1. METRIC (SI) CONVERSION FACTORS

Quantity	To Convert From	To	Multiply By
Length:	in	cm	2.54
	ft	m	0.3048
Area:	in^2	cm^2	6.4516
	ft^2	m^2	0.0929
Volume:	in^3	cm^3	16.39
	ft^3	m^3	0.0283
	gal	m^3	0.0038
Mass (weight):	lb	kg	0.4536
	short ton (ton)	Mg	0.9072
	short ton (ton)	metric ton (t)	0.9072
Pressure:	atm	kPa	101.3
	mm Hg	kPa	0.133
	psia	kPa	6.895
	psig	kPa*	(psig)+14.696)x(6.895)
Temperature:	°F	°C*	(5/9)x(°F-32)
	°C	K*	°C+273.15
Caloric Value; Enthalpy:	Btu/lb	kJ/kg	2.326
	Btu/lbmol	kJ/kgmol	2.326
	kcal/gmol	kJ/kgmol	4.184
Specific-Heat Capacity:	Btu/lb-°F	kJ/kg-°C	4.1868
Density:	lb/ft^3	kg/m^3	16.02
	lb/gal	kg/m^3	119.8
Concentration:	oz/gal	kg/m^3	
	quarts/gal	cm^3/m^3	25,000
Flowrate:	gal/min	m^3/min	0.0038
	gal/day	m^3/day	0.0038
	ft^3/min	m^3/min	0.0283
Velocity:	ft/min	m/min	0.3048
	ft/sec	m/sec	0.3048
Viscosity:	centipoise (CP)	Pa-s (kg/m-s)	0.001

*Calculate as indicated

Source: Adapted from Reference 22.